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JPL PUBLICATION 79-98

Dispersed Storage and Generation Case Studies

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(NASA-CR-162996) DISPERSED STORAGE AND
GENERATION CASE STUDIES (Jet Propulsion
Lab.) 187 p HC A09/MF A01 CSCL 10A

N80-22782

G3/44 Unclas
18043

March 15, 1980

Prepared for
U.S. Department of Energy
Through an agreement with
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by
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FOREWORD

Because the cost of conventional fuels has increased, and for some availability decreased, other means of generating electricity have attracted a great deal of attention, particularly those which use renewable resources, or which make more efficient use of conventional fuels. Many of these new generating sources are either too small or are so geographically dispersed that it is not practical or economical to integrate them at the bulk generation level. They can more suitably be dispersed throughout the system, thus leading to the term Dispersed Storage and Generation (DSG).

Integration, as the term is used here, refers to: (1) connecting the DSG to a utility system in which provisions are made for protection of the DSG as well as the system, and (2) the operation of the DSG as a managed part of the total utility supply system.

To study the implication of the integration of DSG sources into the electric utility system, two distinct parallel efforts were started in 1979 within the Communication and Control Project. First effort was concerned with "Determining the Requirements for Communications, Power Processing, Automation and Control, and Protection derived from the integration of DSG in the Electric Distribution System." The second effort, "DSG Case Studies" is reported in this document.

This report on the case studies is intended to provide an early statement of ways in which technical as well as institutional, environmental, and economic problems have been resolved for specific, near-term DSG applications. The more detailed study, mentioned above, which considers all DSG candidate technologies, is currently being conducted for JPL under DOE funding by the General Electric Company, Schenectady, NY.

ACKNOWLEDGMENTS

This study was conducted as a part of the Communications and Control on the Electric Power System Project which is sponsored by the Electric Energy Systems Division (EES) of the US Department of Energy (DOE) under an interagency agreement with the National Aeronautics and Space Administration, and was administered by Mr. P. Overholt of DOE. The Communication and Control Project Manager is Mr. R. W. Caldwell, and the cognizant JPL Program Manager is Dr. E. P. Framan.

The JPL study participants were: K. Bahrami (Study Leader, Electric Utility Power Systems Group); J. Stallkamp (Electric Utility Power Systems Group); and A. Walton (Economics Group). Substantial contributions were also made by R. W. Caldwell and H. Kirkham.

The authors wish to acknowledge the cordial hospitality of the following people and organizations for the sharing of their valuable time and the needed information which was so crucial for the conduct of this study:

Applied Energy, Inc./ San Diego Gas & Electric Co.	Mr. M. Hale Mr. C. Harmstead Mr. P. Hodiak
California Energy Commission	Mr. S. Burger
Delta Electronics Control Corp.	Mr. C. Jobbins Dr. L. R. Suelzle
Mt. Laguna Air Force Base	Lt. M. E. Hatch Mr. R. Lewis Mr. A. Syverts
New Jersey Public Service Electric & Gas	Mr. C. H. Gentz Mr. R. N. Green Mr. E. A. Hymen Mr. P. A. Lewis Mr. A. Pivec
Niagra Mohawk Power Corporation	Dr. R. Fernandes
Pennsylvania Power & Light Co.	Mr. W. A. Frederick Mr. R. P. Johnson Dr. H. G. Pfeiffer Mr. J. E. Pfluger
Rohr Industries, Inc.	Mr. R. Miller
Southern California Edison	Mr. N. Patapoff

United Technologies Corporation

Mr. L. G. Eklund
Mr. J. M. King
Mr. J. M. Lee
Mr. K. Parkany
Mr. R. Smith
Mr. J. R. Vivirito

We also wish to acknowledge discussions with Mr. J. Rumbaugh of DOE, and the receipt of informational material from the California Public Utility Commission. We are especially grateful to Mr. P. Overholt of DOE for his review and comment on the draft report.

The authors wish to express their appreciation for the assistance rendered by Dr. H. Kirkham of JPL and for his contribution to the text of the report. Last, but not least, we wish to express our gratitude for the efforts of Mr. R. W. Caldwell, Project Manager, Communications and Control Project, for his guidance and support.

ABSTRACT

Three installations utilizing separate Dispersed Storage and Generation (DSG) technologies are selected and analyzed. These are: The 45-kW Pennsylvania Power & Light Co. Wind Turbine Generation System located at Harwood, Pennsylvania; The USAF 60-kW Photovoltaic System located at Mt. Laguna, California; and the 800-kW Applied Energy, Inc./San Diego Gas & Electric Co. Cogeneration System located at Rohr Industries, San Diego, California. Each of these systems is described in detail including connection, site, construction/installation, operation, costs and control. Selected institutional and environmental issues are discussed, including life cycle costs.

No unresolved technical, environmental, or institutional problems were encountered in these installations. The wind and solar photovoltaic DSG were installed for test purposes, and appear to be presently uneconomical. However, a number of factors are decreasing the cost of DSG relative to conventional alternatives, and an increased DSG penetration level may be expected in the future. Consideration should therefore be given to the issues which may be important in the future, including the control/communications requirements and regulatory issues.

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EXECUTIVE SUMMARY

A. BACKGROUND

The desire to increase the amount of electrical energy generated from renewable resources has led to aggressive research and development in a number of new Dispersed Storage and Generation (DSG) technologies. The process of integrating these new DSG technologies into electric utility systems is anticipated to raise a number of technical, institutional, economic, and environmental issues. This case study identifies the issues for three specific, near-term DSG applications, and explores ways in which they have been resolved.

B. OBJECTIVES, APPROACH, AND SELECTION

This case study effort supports the broader program of DSG integration, which is initially directed at defining the functional requirements for integration and operation of DSG technologies in power systems. It also draws upon the information provided by DOE/JPL contractors, the Electric Power Research Institute (EPRI), and other data sources as well as information obtained from the three utilities whose DSG installations are included in this report.

The objectives of this study were:

- (1) To provide documentation of actual and planned installations of DSG.
- (2) To evaluate technical, environmental, institutional and economic factors for each of the cases studied, and
- (3) To generalize the specific factors to provide a framework for the evaluation of other DSG installations, both in terms of the application of the DSG technologies studied here to other systems or geographical areas, in in terms of the extension of these findings to DSG technologies in general.

To achieve these objectives, the following approach was taken:

- (1) Document three DSG installations: include data on technical, institutional, environmental, and economic issues.
- (2) Classify and organize in tabular form the issues documented for the three cases, so as to facilitate cross reference and comparison, and
- (3) Discuss the elements common to all the cases and the issues peculiar to some of them so as to permit the appropriate generalizations to be made.

A number of candidate DSG technologies were considered for this study. They were: Solar Thermal; Solar Photovoltaics; Wind; Fuel Cell; Cogeneration; Battery Storage; Pumped Hydro Storage; Low-Head Hydro; and Water Main Pressure Drops.

Three specific installations based on three DSG technologies from the above list were selected. The selection was based on the following criteria:

- (1) The installation must interface with an electric utility system.
- (2) The installation must be operational, so that maximum benefit can be drawn from the case study.
- (3) The installations selected must represent different types of DSG technologies, so that conclusions generally applicable to DSG systems can be drawn.
- (4) The installation selected should represent new technical and/or institutional challenges.
- (5) The well-documented DOE installations were to be avoided, in order to prevent duplication of effort.
- (6) The installations must be such that the information needed for the study can be obtained.

The three installations selected for case studies are:

- (1) The PP&L 45-kW Wind Turbine Generation (WTG) system in Pennsylvania.
- (2) The 60-kW Photovoltaics System located at Mt. Laguna Air Force Station, Mt. Laguna, California.
- (3) The 800-kW AEI/SDG&E Cogeneration Facility at Rohr Corporation, San Diego, California.

The rationale for the selection of these cases is provided in Section I of this report.

C. THREE CASES STUDIED

1. PP&L 45-kW Wind Turbine Generation System

The Pennsylvania Power and Light Company has found itself in a vulnerable position during the energy and environmental upheavals of the last decade. As new sources of hydropower diminished and additional

pollution regulations were placed upon coal, PP&L diversified into oil and nuclear capacity. But oil supplies have become less secure and more expensive, and nuclear generation faces public opposition. For these reasons, PP&L is interested in supplementing and diversifying its present capacity; it has expressed an interest in exploring cogeneration, and it is currently analyzing the prospects for wind systems.

The 45-kW Wind Turbine Generation (WTG) installation is located at Harwood, Pennsylvania. This installation is a part of an energy research project. The emphasis is on obtaining data and operating experience rather than the generation of electrical energy. Three areas of interest to PP&L were:

- (1) The generation capability of the wind-powered system with time.
- (2) Safety of the interconnection under all operating conditions.
- (3) Interactions with the system that might cause difficulties, particularly with other customers.

The WTG system consists of: a wind turbine which drives a conventional three-phase alternator through a gear box; rectifiers; a line commutated inverter; 500 Ah of battery storage; control and annunciation panel; recording system; metering devices; and protection equipment. The instrumentation includes standard PP&L metering equipment consisting of watt-hour meters at the alternator output and DC inverter input and both watt-hour and VAR-hour meters at the inverter output, and wind speed and direction indicators. Data from these instruments are periodically recorded on magnetic tape with time tags. These tapes are processed on a monthly basis.

The output for the WTG is at 240 Vac, 3 phase. It is connected through three standard single phase distribution transformers (25 kVA each) to the nearby 12 kV PP&L line originating from a sizeable substation less than one-half mile away. The substation is served by 230 kV lines.

The installation is at about the 1800-ft. elevation on a plateau atop a mountain range at the location of a former generating station. The immediate surrounding area was cleared of trees and brush. The equipment site itself was fenced, a ground wire grid installed and gravel placed in the enclosed area. Access is controlled by a locked gate and the installation has been equipped with the required electrical and mechanical interlocks and safety precautions.

The fenced site is 125 feet (N-S) by 100 feet (E-W) with the wind turbine located in the north end. A 12 ft. x 12 ft. prefabricated building located in the south end is the control house.

The WTG system started its initial operation on October 12, 1978. About 90 hours of data has so far been taken at 30 different times from which the average wind speed was determined to be approximately 11 mph. During this period of time 170 kWh of energy was fed into the power system, whereas 340 kVARh of reactive load was drawn from the line. The average rates were 1.7 kW and 3.4 kVAR, respectively.

This WTG is an excellent test bed for a variety of experiments that could simulate a range of practical situations. Currently this installation uses battery storage, which acts as an intermediary between the highly variable wind-generated power, and the power which is fed to the utility line.

PP&L has near-term plans to directly feed the power from the alternator to the line, without rectification and subsequent inversion. This will improve the efficiency of the system and represents a lower-cost approach. However, it may require a more complicated synchronization method.

Extensive test plans have been made for the scheduled two years of operation. Most of the time the operation will be unattended, although some manual testing is planned. There is the possibility of installing a solar photovoltaic cell array at the site.

The objectives of the PP&L wind system were to obtain information and to gain operational experience with the WTG. A review of the initial capital costs, site preparation expenses, recurring costs, and a number of assumptions regarding the price of alternatives and general economic conditions shows that the WTG installed at PP&L was not a profitable investment. However, the prime motivations for the PP&L installation were the long-run assessment of interfacing with a wind system, and the development of contractual guidelines and requirements for future WTG systems, rather than increasing the profitability of the existing system.

The licensing process was relatively problem-free. The PP&L wind system had to conform to a number of local building and safety codes, but these did not delay installation. Environmental impacts of the system were considered minimal, and mostly visual; because of the visual impact, esthetics were considered in the design.

2. 60-kW Photovoltaics System at Mt. Laguna

The 60-kW photovoltaics (PV) system selected for this study was initially located at the Delta Electronics Control Corporation facility in Irvine, California, where it was connected to the Southern California Edison system. Later, it was moved to its permanent location at Mt. Laguna Air Force Base, Mt. Laguna, California. In this location, it is connected to the power system at the USAF base. The latter uses diesel-powered generators to supply its electrical needs, which average 750 kW. The monthly usage of electricity at the base is approximately 500,000 kWh, corresponding to approximately 40,000 gallons of diesel fuel.

The PV installation at Mt. Laguna uses 2366 solar cell modules manufactured by Solar Power and Solarex. The collection voltage is 230 Vdc. The positive and negative leads of 169 series string of modules are brought in separately through a paralleling and monitoring panel to a power processor unit. Within this panel there is a power processor which consists of: 1) A dc voltage limiter; 2) A self-commutated inverter, and; 3) Automatic shutdown and start-up equipment.

During the testing phase, when the PV system was connected to the SCE system, the output from the power processor was connected to Delta Electronics Control Corporation's main 480 V, 3-phase distribution feeder.

The Mt. Laguna PV system site is 170 ft. x 190 ft. and has been leveled and fenced. There is controlled public access to the facility. There is a considerable amount of rain (typically 50 inches/year) at the site, resulting in a cleaning action on the solar panels.

The prefabricated mounting frames of the cell modules, which are atop vertical wood supports installed in concrete footings, are of galvanized heavy steel construction. The power conditioning and control, and the protection and metering gear are housed in a small concrete block building adjacent to the array.

The operation of the PV system including solar array, power conversion system, start-up, synchronization, and shutdown is automatic. An operator at the power house can manually disconnect the PV system from the power grid. The normal direction of power flow is from the PV system into the line. However, there may be cases of power flow from the line into the PV system. This power flow is limited to a maximum of 3 kW for less than 8 minutes. Currently, no control and/or monitoring information is sent from the PV system to the power house control room. It is planned that, in the near future, a system on/off indicator be installed.

The effect of the PV system on the operation of the Air Force base power system is small. This is due to the fact that: 1) The operators are accustomed to fast and large variations due to changes in AFB radar loads, and; 2) The variation in the output of the PV system is generally not fast. The PV system has been in operation a short time and data from actual operation are now being taken.

The Mt. Laguna photovoltaic project was installed for informational and demonstration reasons, rather than profit motives. A financial analysis included in this report indicates that the installation would be commercially unprofitable. Southern California Edison is experimenting with a number of rate schedules and buy-back arrangements for dispersed power generation. While different rate structures and ownership arrangements do change the apparent value of the system, the current cost of the PV array is not justified by savings of fuel or capacity.

No problems were encountered in installing and operating the PV system through the time of our site visit. The initial system testing was done on Delta Electronics property, and later operation has been carried out on government land at Mt. Laguna. The main interaction with regulatory agencies occurred when Delta and SCE entered into a parallel generation agreement; the agreement was not effective until California Public Utility Commission Approval was received.

Southern California Edison does not have immediate capacity problems, but its future expansion is hampered by a number of increasingly-strict air quality regulations. In addition, a large portion of SCE's planned capacity additions are nuclear generators, and a number of California laws contain stringent requirements on the construction of nuclear power plants. These regulations have induced SCE to seek out alternative forms of generation.

3. SDG&E 800-kW Cogeneration System

The 800-kW gas-turbine generator with waste heat recovery for production of process steam is located at the Rohr Corporation plant in Chula Vista, California. It is a commercial installation utilizing cogeneration to the mutual benefit of the utility and the manufacturing company.

There is a three-way contract among SDG&E, Applied Energy, and Rohr. Applied Energy, a subsidiary of SDG&E, handles all of the cogeneration activities of the parent utility; there are several ongoing cogeneration operations, principally involving the U.S. Navy in the San Diego area. In the Rohr plant case studied here, SDG&E owns and operates the gas-turbine generator unit, which is located on Rohr plant property, through a lease agreement. Waste heat is sold to Applied Energy; the latter generates steam which is sold to Rohr.

The gas-turbine generator is a Saturn model built by Solar Corporation of San Diego. The electrical power generated is fed through step-up transformers directly to the 3-phase 12 kV utility line. Since the Rohr plant electrical load is about 5 MW, the locally generated power is effectively used on-site. The unit is controlled from a SDG&E location in downtown San Diego about 7 miles away.

Steam requirements at the Rohr plant are such that the turbine generator plant operates continuously; in fact, this is considered base load capacity by the utility. Steam load variations associated with shift changes and meal breaks are completely absorbed by the steam system reservoir capacity; on Sundays and holidays when the steam load is less than normal, steam can be vented, or the gas-turbine unit operated at a reduced level, since the Rohr plant electrical load is also very much less at those times. Rohr maintains standby boilers for maintenance times on the gas-turbine unit; during winter months the plant steam requirements exceed that available from the cogeneration unit and the boilers are operated.

One special feature of this installation is the provision of emergency power to the Rohr computer complex. In case of outage of the normal utility service, the output of the gas-turbine unit is isolated from the out-of-service utility line and enters the Rohr plant via a separate circuit. Inside the plant, the computer complex load is then connected to this emergency source. SDG&E installed and maintains the additional equipment, and charges Rohr for this special service under a deviation from tariffs filed with the California Public Utilities Commission.

Operation started in February, 1979, and there have been no serious difficulties. Apart from a planned control system update to provide additional and more accurate status information at the remote downtown San Diego control site, no changes are anticipated.

This case was the one in which the primary motivations were economic - to increase the power output from expensive fossil fuels, to limit the costs of electricity failure or natural gas cutoffs, to augment electricity capacity. The cogeneration arrangement was motivated by institutional and environmental problems facing SDG&E.

The financial analysis contained in Section II of this report explores a scenario under which the cogenerator owned all the equipment, purchased fuels, and sold by-product steam and electricity. In this case study, those functions were divided among the three parties involved. SDG&E owned the turbine equipment and "purchased" the electricity from the generation process by giving AEI a credit for the Btu equivalent of the output. AEI acted as a steam contractor: it operated the turbines and sold the steam output to Rohr.

The main benefits to Rohr came from a pair of contractual options which made the company's electric and fuel supplies more secure. The first option allows Rohr to use the 800-kW generating capacity for its computer operations in the event of a power failure. Secondly, Rohr is on interruptible gas service; if its gas service were cut off, Rohr could continue its operations by using fuel stored for use by the cogeneration turbines. If these options had not been available, Rohr would have had to build a back-up system for service to the computer facility, and an oil back-up facility.

Some problems and delays in setting up the Rohr facility were related to environmental regulations. Three programs currently administered by the Environmental Protection Agency (EPA) specify maximum pollution levels for new or modified stationary sources, including fossil-fuel-fired steam generators. The standards apply to fossil-fuel-fired boilers of more than 250 million Btu per hour of heat input. The Rohr facility is the largest generator which can meet the Air Pollution Control District (APCD) rules for the levels of contaminant in the air without the use of scrubbers. Although it took a long time to get the APCD permit, the AEI facility does not need scrubbers. In addition, since the AEI facility is on Rohr property, a problem of liability and

access arises, which so far has been resolved by having AEI personnel (rather than Rohr personnel) check the facility each day.

Of the three utilities studied, SDG&E is faced with the greatest capacity problems. The inexpensive hydropower it has been buying from the Northwest may not be available after the mid-1980s. Progress on the Sundesert nuclear facility has been halted, and plans to repower an oil-fired unit have been cancelled. Thus, SDG&E is trying to pursue a variety of options to fill future capacity and energy needs.

The Rohr facility presents an opportunity for cogeneration because it requires large amounts of steam continuously. From the utility side, SDG&E has had considerable experience in the operation of small dispersed units of oil and gas-fired turbines. This combination of operating characteristics and operating experience made the Rohr-AEI cogeneration arrangement a mutually beneficial one.

D. SUMMARY OF ANALYSIS

1. Synthesis of Issues

The issues which arose during the design, installation, and operation of each DSG system are presented in Tables ES3-1 through ES3-4, and described in the associated text. The tables also include issues which may be faced by future applications of other DSG systems, but were not encountered here.

a. Technical. Table ES3-1 presents the technical problems encountered by each DSG system. These were divided into four main categories:

- (1) Design Considerations - no special design considerations appeared in the cogeneration case. The PV and WTG systems used dc-to-ac inverters, and required security fencing. Spacing of PV arrays for access was a design consideration.
- (2) Operation - resource availability was an issue in all three cases; for PV and WTG, the resource is intermittent and essentially uncontrollable, while the availability and quality of waste heat was important in the cogeneration case. Since the PV system represented a significant portion of Mt. Laguna's system capacity, the question of power system stability was raised, but was not found to be a problem in this case. Abnormal wind conditions could occur for the WTG; the system was constructed to enable safe operation through such conditions. In addition, short term resource stability is important in the case of the WTG, where gusting can change the power available in a matter of seconds.

Table ES3-1. Technical Issues

ISSUE	WTG	PV	COGEN
<u>DESIGN CONSIDERATIONS</u>			
INVERTER TYPE	X	X	
SECURITY FENCING, SPACING	X	X	
GROUNDING		X	
AUXILIARY EQUIPMENT UNIQUENESS			
<u>OPERATION</u>			
AVAILABILITY OF RESOURCE	X	X	X
LOADING-BASE/INTERMEDIATE/PEAK	X	X	X
STORAGE	X		
POWER INFEEED NOT PERMITTED		(X)	
STABILITY OF UTILITY SYSTEM		X	
MANNED/UNMANNED			
REAL-TIME MONITORING	X	X	
RECORDING			
ABNORMAL CONDITIONS	X		
HARMONICS			
SHORT-TERM STABILITY OF RESOURCE	X		
<u>MAINTENANCE</u>			
ICING OF BLADES	X		
FREQUENCY			
COMPLEXITY			
RESPONSIBILITY			X
REPLACEMENT PARTS/HARDWARE			
<u>PROTECTION</u>			
UTILITY SYSTEM	X	(X)	X
DSG SYSTEM	X	X	X
LEGEND: X = EXPLICITLY IDENTIFIED BY ORGANIZATIONS CONCERNED.			
(X) = TRUE AT DECC AND NOT AT MT. LAGUNA AFS.			

Table ES3-2. Cost Components

COMPONENT	WTG	PV	COGEN
<u>SYSTEM COSTS</u>			
<u>RECURRENT COSTS</u>			
OPERATION			X
MAINTENANCE			X
FUEL INPUT			X
ELECTRICITY			X
<u>NONRECURRENT COSTS</u>			
INITIAL INVESTMENT			X
SAFETY EQUIPMENT			X
ENVIRONMENTAL ADDITIONS			
INSTALLATION/SITE PREPARATION	X		X
PERMIT PROCESS			X
BACK-UP EQUIPMENT			
<u>SPECIAL EQUIPMENT COSTS</u>			
(Costs of equipment used for testing and information gathering, which is not essential for operation)			
DATA ACQUISITION EQUIPMENT	X	X	
CONTROL OR PROTECTION SYSTEM			
CHANGES TO FACILITATE TESTS	X	X	
LEGEND: X = Explicitly identified by organizations concerned.			

Table ES3-3. Environmental Issues

ISSUE	WTG	PV	COGEN
<u>POLLUTION</u>			
AIR			X
WATER			
AUDIBLE NOISE	X		X
RADIO/TV INTERFERENCE	X		
VISUAL	X		
LOW FREQUENCY ELECTRIC FIELD			
<u>WASTE DISPOSAL</u>			
<u>LAND USE</u>			
<u>ECOLOGY - BIOSYSTEMS</u>			
FLORA			
FAUNA	X (BIRDS)		

LEGEND: X = Explicitly identified by organizations concerned.

Table ES3-4. Economic/Institutional Issues

ISSUE	WTG	PV	COGEN
<u>SAFETY/LIABILITY</u>	X	X	X
<u>REGULATIONS</u>			
ZONING LAWS	X	X	X
EIS			X
RATE STRUCTURE/REVIEW			X
TAX ARRANGEMENTS			X
FUEL USE LAWS			X
<u>PUBLIC ACCEPTANCE</u>			
<u>INFRASTRUCTURE</u>			
(Utility Organization, Personnel Assignments)			

LEGEND: X = Explicitly identified by organizations concerned.

- (3) Maintenance - with the exception of cogeneration, where the division of responsibility for maintenance was delineated between the parties involved, the maintenance of equipment was not considered to be an issue.
- (4) Protection - all three DSG systems raised issues concerning the protection and operation of the utility system to which they were connected. Similarly, protection of the DSG from power system problems was also important. These problems were not particularly difficult technically to solve. For PV, grounding of the system was considered important for safety reasons.

b. Cost Components. All items of expenditure which affect the cost of an installation are listed in Table ES3-2. Recurrent costs include expenditures made throughout the system lifetime; the category also includes anticipated increases in these costs over time. Thus, expected increases in the price of fuel and electricity were important considerations in the cogeneration case; operating and maintenance arrangements were also taken into account. However, since the wind generation and photovoltaics systems were primarily test sites, these recurrent costs are not well known, and were not primary considerations when installing the systems.

Non-recurrent costs include all expenditures necessary to make the DSG system operable. While the main costs are usually basic equipment costs, there are also expenditures associated with obtaining zoning and environmental permits, site and foundation preparation, and safety and back-up equipment. Although the cogeneration facility had to file an environmental impact statement (included under the permit process category), no additional environmental equipment was necessary. However, all other non-recurrent costs were important in the installation of the cogeneration facility. Many of these cost considerations were not important for the other two case studies; since these were prototype systems, basic equipment costs and permit procedures were not yet standardized. While these costs will be important to future wind and photovoltaic systems, they were not central considerations here.

The final cost category includes special equipment which is not essential for the operation of a DSG system. This includes equipment used for data acquisition and processing, and equipment additions used to protect the system while tests are underway. Special equipment was a significant part of the system cost for the wind turbine and photovoltaic facilities.

c. Environmental Issues. The environmental issues are summarized in Table ES3-3. The various forms of pollution are a major part of this category. The cogeneration facility had to conform to California's air quality standards; audible noise was also a consideration at the Rohr facility. Pollution problems for the wind turbine focused on audible noise, radio and TV interference, and the visual aspects of the turbine design.

Another consideration is the effect of a new DSG system on the surrounding animal and plant life. In these three case studies, the only effect identified was that of bird migration upon the wind turbine generation system.

d. Economic/Institutional Issues. The first issue in this category, which is tabulated in Table ES3-4, is safety. Protection of the utility and DSG system were discussed under technical issues, and they are not considered here. This category focuses upon the liability problems which must be resolved when a small power producer is connected to the local utility. For all three facilities, this was an important consideration. The cogeneration facility was faced with an unusual issue. This was whether Rohr Industries personnel should or should not maintain the equipment connected to the utility. All three facilities had to consider safety hazards to the surrounding community.

The second category includes the wide variety of regulations under which each system must operate. All three facilities had to consider local zoning ordinances when locating the facility. An environmental impact statement (EIS) was required for the cogeneration facility.

For Rohr Industries the possible cutoff of natural gas was an important consideration in the decision to enter into a contract involving cogeneration.

2. Extension to Other Applications and DSG Technologies

Due to the experimental nature of these wind and PV installations examined and the low levels of DSG penetration, not all of the issues listed in Tables ES3-1 through 3-4 were issues for these three cases. If penetration levels remain low, it may be that only the issues outlined in Section III.B will be pertinent to the installation of similar DSG technologies in other applications. For wind systems these issues include: resource availability, site selection, power processing, environmental considerations, capital costs, and public acceptance. The main considerations for photovoltaics are weather conditions, environmental impacts, power processing, cost reduction, and public acceptance. Since cogeneration is beyond the experimental stages, the major issues are availability of primary fuels and waste heat, contractual arrangements, local environmental regulations, and liability concerns.

At the present time, due to their small numbers and size, dispersed storage and generation installations have had a negligible effect on the operation of utilities. However, higher penetrations of dispersed generation may make issues out of impacts that went unnoticed at lower penetration levels. It seems impractical to handle an increasingly large number of DSG installations on an individual basis, with case-by-case exceptions to the established regulations. These possible issues are addressed in the final portion of Section III, and include:

- (a) Technical Considerations - the installation of a large number of small generators whose output is essentially uncontrolled

(because output depends upon the sun or the wind) under abnormal system conditions will almost certainly require some degree of monitoring and control capability. This capability will undoubtedly have benefits to the system in its normal state (for example, the possibility of voltage control using DSG) and may be necessary under other system states, e.g., restorative, but may impose a severe burden on the communication and control system because of the large number of sources that a high penetration represents. Suitable control and communication methods and appropriate control strategies must be developed along with the DSG technologies.

- (b) Pricing Agreements Between the User and the Utility - currently, systems which are jointly owned or operated resolve contractual agreements on a case-by-case basis. However, pending rule-making proceedings under PURPA will set guidelines for purchase and sales prices of electricity between small power producers and utilities, as well as back-up and stand-by agreements. Application of new rules and regulations for pricing may require new data acquisition and control systems, particularly for those generators over 10 kW in size.
- (c) Liability and Safety Considerations - liability and safety considerations become issues when a DSG technology is jointly owned or operated. These problems are also being resolved on a case-by-case basis.
- (d) Regulations - zoning laws and building codes may become more restrictive. Environmental impact statements may be a prerequisite for non-experimental units. (See also (b) above)
- (e) Waste Disposal - some proposed DSG systems use toxic or hazardous materials to produce energy. Provisions must be made to safely dispose of these materials at the end of the substance or DSG system lifetime.
- (f) Land Usage - widespread adoption of DSG systems may compete with alternative land uses, such as residential, recreational, or agricultural purposes.

E. CONCLUSION

Three cases of dispersed storage and operation (DSG) have been studied. A variety of energy sources and generation technologies were represented. Broadly speaking, no unresolved technical, environmental or institutional problems were encountered in these installations. The photovoltaic and wind DSGs were installed for test purposes, and appeared to be presently uneconomical. However, a number of factors are decreasing the cost of DSG relative to the alternatives, and an increased penetration level may be expected in the future. Consideration should therefore be given to the issues which may then be important, including the control/communications requirements and the regulatory issues.

SECTION I

BACKGROUND AND SELECTION

A. OBJECTIVES

The process of integrating new dispersed storage and generation (DSG) technologies into existing electric power systems will raise a number of technical, institutional, economic, and environmental issues. This Case Study effort explores ways in which these issues may be resolved for specific, near-term DSG applications. It is not intended to replace the more detailed studies which will consider all DSG candidate technologies.

This Case Study effort will support the broader program of DSG integration, which is initially directed at defining the functional requirements for integration and operation of DSG technologies in power systems. It also draws upon the information provided by DOE/JPL contractors, the Electric Power Research Institute (EPRI), and other data sources, as well as information obtained from the three utilities whose DSG installations are included in this report.

The objectives of this study were:

- (1) To provide documentation of actual and planned installations of DSG.
- (2) To evaluate technical, environmental, institutional and economic considerations for each of the cases studied, and
- (3) To generalize the specific considerations to provide a framework for the evaluation of other DSG installations, both in terms of the application of the DSG technologies studied here to other systems or geographical areas, and in terms of the extension of these findings to DSG technologies in general.

To achieve these objectives, the following approach was taken:

- (1) Document three DSG installations: include data on technical, institutional, environmental and economic issues.
- (2) Classify and organize in tabular form the issues documented for the three cases, so as to facilitate cross reference and comparison, and
- (3) Discuss the elements common to all the cases and the issues peculiar to some of them so as to permit the appropriate generalizations to be made.

Section I-B, below, lists the candidate DSG technologies considered in this study, and the reasons for choosing the three cases analyzed further in Section II. This does not represent a comprehensive list of possibilities; it is an estimate of technologies which will be available in the near future, based upon current information.

B. OVERVIEW OF POTENTIAL DSG SYSTEMS

1. Candidate DSG Technologies

In general, Dispersed Storage and Generation (DSG) may be defined as any source of electrical energy (including storage elements which act as sources at times) connected directly to a utility distribution system.

An essential part of this definition is the connection to the distribution part of the electricity supply system. Because the power ratings of distribution system hardware are smaller than the ratings of transmission equipment, it follows that the power rating of DSG is also smaller. However, a DSG connected to the subtransmission system of a large company may be larger than a "central station" generator at a small company.

Electric generators are customarily interconnected by a transmission system, which allows for the most economical use of available generation resources as the load and the availability of generators change. Often, the transmission system is designed to carry large blocks of power from an area with generation capacity to an area of load.

This situation contrasts with the anticipated use of DSG. Connected to the distribution system, which is generally a radial system, DSG is not likely to be used to supply remote loads. A high penetration of DSG could, of course, change transmission line loading. However, it is unlikely for radial distribution to function as a power collection network to feed power to a transmission system.

Neither size nor impact on the utility system may be used alone as a criterion to identify dispersed storage and generation. DSG may be considered to have some (generally more than one) of the following elements:

- (1) Small size (less than 50MW).
- (2) Contains storage.
- (3) Intermittent source (such as sunlight or wind).
- (4) Connected to subtransmission or distribution systems.
- (5) Fuel or energy source dispersed or uniquely available at site.

Prior to the selection of the three DSG installations for this report, probable DSG technologies were surveyed to determine the most suitable installations. Since this report deals only with near-term technologies, no consideration was given to possible DSGs which are still in the early state of development. The technologies considered, and the projects involving these technologies, are as follows:

a. Solar Thermal. Solar thermal generation may use a central receiver or dispersed receivers. A central receiver plant consists of a field of sun-tracking mirrors (heliostats) which focus the solar radiation on a receiver located on a tower (Power Tower). The receiver converts solar radiation to heat which is then transported, by some fluid, to a generator driven by a heat engine. The heat engine may be a Brayton cycle, a Rankine cycle, or a combined cycle machine. In the dispersed receiver case, plants consist of a grouping of individual, comparatively small solar-thermal energy conversion devices. Each device contains a concentrating element (typically a parabolic dish mirror, but it can also be a parabolic trough or even a lens) and a receiver to convert the solar radiation to heat. The heat energy can be converted to electricity at the individual receiver or it can be gathered to a central point for conversion to electricity. Each element would have an output in the 10 kWe to 100 kWe range.

The only existing "power tower" facility is at Albuquerque, New Mexico. It is a joint effort by the Department of Energy, the Electric Power Research Institute, and Sandia Corporation (Ref. 1). At the present time, it is being used for component tests and does not generate electricity. However, there are plans for a 10 MWe central receiver facility to be built at Barstow, California by Southern California Edison, the Los Angeles Department of Water and Power and the D.O.E. This facility is scheduled for completion in 1981 or 1982 (Ref. 2). Although there are a variety of dispersed receiver projects under way, the first demonstration plants for the generation of electricity will not be in operation until the early 1980s (Ref. 3).

b. Photovoltaic. Photovoltaic units may be of a non-concentrating or concentrating type, utilizing silicon or other types of cells (Ref. 3). The standard, flat silicon cell array is the most mature of photovoltaic technologies and is the object of a DOE cost reduction program attempting to reduce cell costs to \$700/kW by 1986 (in 1980 dollars). Present costs of these cells, approximately \$8,000/kW, make them unattractive except under unusual circumstances. Present day installation of solar cells are generally in remote areas where conventional energy sources are unavailable.

Two projects under way which involve photovoltaics in utility-type applications are described here. One, sponsored by the Department of Defense and DOE, is a 60 kW system for use at a remote radar site at Mt. Laguna AFB (Refs. 4,5). From January to June, 1979, it was demonstrated on Southern California Edison's system. The other project, also with DOE sponsorship, is to be installed in the second half of 1979 at Mississippi County Community College in Arkansas. This will be a 300 kW system and will run in parallel with Arkansas Power and Light (Ref. 6).

A variety of photovoltaics technologies are under investigation. Materials such as gallium arsenide and cadmium sulfide are being considered. The use of concentrators similar to the dispersed receiver solar thermal devices is under investigation. Thermovoltaic cells, which combine photovoltaic generation with a heat cycle, are also being experimented with. However, it does not appear that any of these will be in demonstration installations during the next few years.

c. Wind Turbine. The wind turbine is an energy conversion device which has been used for various tasks for many years. The present renewed interest in using wind turbines for generating electricity has precipitated public and private funding of a number of operating machines.

DOE has sponsored, under NASA management, a series of wind turbine generators (WTGs). The first one, MOD-0, was the NASA - Lewis Research Center demonstration unit (Ref. 7). Subsequent machines (MOD-0A) have been installed at Clayton, N.M. (Ref. 41), Culebra, Puerto Rico and Block Island, New York. The MOD-0A machines are all 200 kW devices. Larger machines are planned for Boone, North Carolina (MOD-1 at 2 MW), and Palm Springs, California (3 MW). These machines will be operational by Summer, 1979 and 1981, respectively (Ref. 8).

There are also a number of privately owned WTGs. There is a 200 kW machine on Cuttyhunk Island, Massachusetts which has been operating for about a year (Ref. 9). Four WTGs are connected to Pennsylvania Power and Light's generation system; one of these, rated at 45 kW, was installed by Pennsylvania Power and Light (Ref. 10, 11).

d. Fuel Cell. The fuel cell is a technology which came out of the space program: electricity is generated directly from a chemical reaction. The cells which are presently being built are the Hydrogen-air type, which require natural gas or distillate for fuel. United Technology, DOE, EPRI and Consolidated Edison Company are installing a phosphoric acid fuel cell on Con Ed's system in Manhattan, New York. It will have an output of 4.5 MW (AC) and will be completed later in 1979 (Refs. 12 through 22). More advanced cells, which are still under development, include the Molten Carbonate type which is projected to use coal derived fuels.

e. Cogeneration. Cogeneration is the simultaneous generation of electricity and useful heat from a common facility. Such a system is capable of a much higher overall thermal efficiency than can be achieved by separate systems. Cogeneration is an old technique, but it became uneconomical with the advent of large, central power plants and inexpensive fuels.

There is a considerable potential for cogeneration in the U.S. The potential for cogeneration for California has been previously investigated (Ref. 23). Because of rapidly rising fuel prices, cogeneration has recently received renewed interest. A number of utilities are actively looking for suitable applications for cogeneration on their systems. There are a number of installations in the Pacific Northwest (where cogeneration has continued to exist) at pulp mills. There are also installations associated with petroleum refineries, for example Southwest Public Service in Texas, and with other manufacturing plants which use process heat (Ref. 24). San Diego Gas and Electric has set up a subsidiary company, Applied Energy, Inc., specifically to promote cogeneration.

f. Battery Storage. One of the major challenges for the electric utility industry centers around the fact that the demand for electricity is not constant, but fluctuates during the day. This creates a problem for utility expansion planning because portions of installed generating capacity will not be used during part of the day. When a power plant is not running it is not generating revenue. If, through the use of storage, the amount of electricity generated would be made more nearly constant, the equipment would be utilized more efficiently and more economically.

There have been many proposals as to how this could be done. The storage battery has some additional characteristics which are very desirable to the utility, such as quick response, and so EPRI, DOE, and Public Service Electric and Gas, New Jersey are involved in a project to demonstrate the usefulness of storage batteries. The Battery Energy Storage Test (BEST) facility is under construction in New Jersey and will be completed by the end of 1979 (Refs. 25 through 39). The objectives of the BEST project are (Ref. 30): a) Provide a focus for the development of battery systems including AC-DC power conversion equipment, b) Provide the necessary independent test data over a wide range of operating conditions to verify expected battery system performance, c) Permit comparison of different advanced battery systems under nearly identical test conditions, and d) Allow evaluation of battery system performance in the utility environment at an early state of battery system development. It will initially use lead-acid batteries, and then other advanced batteries as they become available.

g. Pumped Hydro Storage. Another energy storage technique is pumped hydro. As it is presently used, pumped hydro consists of a reservoir and a power house with turbine/generator units. The only difference between this and any normal hydro-electric installation is that the turbine/generators can be used to pump water back into the reservoir. There are a number of pumped hydro installations in operation and they generally have an energy-in/energy-out efficiency of approximately 70%. However, at the present time they are site limited, as is conventional hydro power. There have been proposals made for flat land pumped hydro using underground caverns, but this has yet to be demonstrated.

h. Low-Head Hydro. Low-head hydro power is another old technique. A familiar example would be the water wheel driven grist mill in 19th century New England. The connection of a low-head hydro to a utility poses no new technical problems; it is essentially the same as conventional hydro.

There is a new 7.2 MW low-head hydro facility at Idaho Falls, Idaho which is 50% funded by DOE. The completion date was summer, 1979.

i. Water Main Pressure Drops. It is a characteristic of the western United States that water for the cities must be transported long distances. This water undergoes large elevation changes during its journey. Energy is expended to raise the elevation of the water, and there is energy to be recovered when it drops back down. It has become common to install hydro generation on the "down hill" side of large water projects. However, there are other pressure drops in the main and distribution systems which have the potential of providing energy in the MWe range. These are presently being investigated by Southern California Edison and Los Angeles Department of Water and Power.

2. Selection Criteria

From this lengthy list of energy technologies, a manageable number of case studies had to be chosen for in-depth analysis. Six criteria were used to select three energy systems. The criteria established are as follows.

- (1) Interface with Utility System - As one of the goals of the Case Studies is to look at the problems associated with controlling a DSG on a utility system, it is necessary that the DSG be connected to and controlled within the host utility. Very little could be gained in this area by studying a DSG which is not utility connected.
- (2) Operational - It is obvious that more is known about a system after it has been running for a time than was known before it was built. However, it is also realized that the DSGs are inherently new and, generally, are not yet commercial. It was therefore decided that operational experience would be desirable, but lack of it would not automatically exclude a particular DSG.

- (3) Different DSG Types - As one of the objectives of the Case Study effort is to draw conclusions which are generally applicable to DSGs, the three subjects should each be a different type of DSG. This would give the widest possible range of problems and solutions.
- (4) New Technological and/or Institutional Challenges - All DSGs raise technical, institutional, and economical issues in their application on the utility system. However, it is not necessarily true that these problems apply to the DSG/utility interface.

It was decided that, regardless of how interesting an installation might otherwise be, there would be no point in including it in the study if there was nothing to be learned from the interface and controls.

- (5) Documentation - The well-documented DOE installations to be avoided, in order to prevent duplication of effort.
- (6) Accessibility - To obtain the depth of information needed for this study, the people involved with each installation should be open and willing to discuss their experiences and ideas for the future. (This was not a problem. Everyone contacted was most cooperative.)

3. The Selected DSG Installations

The following is a brief description of each of the three DSG installations selected for this study along with an outline of why each was selected.

a. Wind Turbine. Because of the large amount of public interest in WTGs and because there is a comparatively large amount of operating information available it was hoped that a WTG could be found for this study. The main difficulty with most of the WTG installations is that they are connected to small, diesel powered systems; these systems are not typical in either control or regulation. Such installations provide the WTG designers with information about the machine and its interaction with a system to which it is a major contributor. (200 kW would not make much of an impact on a 5,000 MW system, but it can interact noticeably with a 1500 kW system.)

Pennsylvania Power and Light (PP&L) has installed a 45 kW WTG on their system. It was felt that this installation was worthy of study for a number of reasons:

- (1) It is an AC-DC-AC power link system which differs from the majority of other WTGs which are primarily AC only.

- (2) The operating characteristics of the machine were well documented by PP&L (Ref. 11).
- (3) PP&L has three private machines on their system and has gained valuable experience with them.

b. Photovoltaic. The 60 kW photovoltaic installation which, for the first part of 1979, was installed at Delta Electronic Control Corporation (DECC) in Irvine, California, was chosen as one of the three subjects. It is a Department of Defense project with part of the funding coming from the Department of Energy. Its intended use is at the Mt. Laguna AFB remote radar site where it offsets existing diesel powered generation. (Refs. 4, 5). DECC has the responsibility for the design and manufacture of the power processor and for the installation of the equipment at Mt. Laguna AFB. As a demonstration of the system, the power processor and part of the photovoltaic arrays were set up at DECC's facility in January of 1979 and connected in parallel to the incoming Southern California Edison feeder. The installation thus became, to our knowledge, the only photovoltaic system of any significant size connected to a utility.

Although this system was not actually conceived as a utility connected DSG, the fact that it had utility connections for a period of six months led us to select it for study.

c. Cogeneration. Cogeneration is another technology for which there is a great deal of operating experience. It is also one which is known to have the potential for significant, near-term applications.

San Diego Gas and Electric's (SDG&E) Rohr Corporation installation was chosen from among the many cogeneration installations in the United States for the following reasons:

- (1) SDG&E has demonstrated an interest in future cogeneration by setting up a subsidiary, Applied Energy, Inc., to encourage cogeneration.
- (2) The Rohr installation used readily available equipment.
- (3) SDG&E is relatively close to JPL.

SECTION II

CASE STUDIES

This portion of the report analyzes three specific DSG installations: the wind generation system at Pennsylvania Power and Light, the photovoltaic system for Mt. Laguna AFB, and the cogeneration system in San Diego Gas and Electric. For each of these installations a detailed description of the DSG system and a description of the utility system in which the DSG is located is provided. The next two subsections draw heavily upon information gained through interviews with utility representatives. Each subsection focuses upon the reasons why a specific DSG was chosen, the benefits each DSG installation created, as well as the problems each system brought to light.

A. WIND GENERATION

1. Introduction

Pennsylvania Power and Light Company (PP&L) serves a 10,000-square-mile section of Pennsylvania which includes Allentown, Bethlehem, Harrisburg, Lancaster, and many small towns. PP&L is a winter peaking utility due to the use of electricity for heating. For ease of comparison, general information on all the three utilities is presented in Table 1-1.

Until recently, coal and hydropower were the only energy sources for electricity production. PP&L has a wholly-owned subsidiary, Pennsylvania Mines Corp. (PMC), which provides the utility with a fairly secure supply of coal. In 1977 PMC gained full control of The Oneida Mining Co., but abandoned underground mining operations in August 1978 due to poor mining conditions, low production, and high coal costs. Because of the cost, safety, environmental, and labor problems associated with coal, PP&L has tried to diversify the energy input base from which it derives electricity.

To enhance its ability to handle peak loads, PP&L built a number of oil-fired units at the Martins Creek plant, which is above Easton on the Delaware River. The first of these oil-fired steam units began commercial operation in 1975; testing on the second unit began in 1976. The Martins Creek generating plant is the largest on the PP&L system, with a capability of 1,940 MW. This is a significant proportion of PP&L's total capacity.

PP&L has also begun to invest in nuclear power. Construction of the Susquehanna nuclear plant near Berwick has been a major portion of the utility's efforts in the past few years. At the end of 1978, the nuclear plant was about two-thirds complete, with commercial operation of its two 1,050 MW units scheduled for 1981 and 1982, respectively.

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Table 2-1. Comparative Statistics for 1977*

	<u>PP&L</u>	<u>SCE</u>	<u>SDG&E</u>
Service Area (sq. mi.)	10,000	50,000	4,400
Electricity Customers (#)	954,613	2,900,856	682,946
Residential	839,852	2,572,826	613,886
Commercial	107,165	234,276	61,060
Industrial	6,174	33,791	7,171
Agricultural	--	25,888	--
Other	1,422	34,075	--
Other Customers	592	--	461,956
	(Steam)		(gas)
Electricity Sales (kWh x 10 ³)	21,200,609	57,726,275	8,676,314
Revenue Mix (%)			
Residential	40%	30%	39%
Commercial	27%	25%	23%
Industrial	28%	23%	35%
Other	5%	22%	3%
Capacity as of 1/1/78 (MW)	6,877	14,337	2,105
Peak Demand (MW)			
Summer	3,385	11,247	1,746
Winter	4,514	8,925	1,667
Generation - Energy Inputs (% of Total)			
Coal	79%	14%	--
Oil	19%	56%	73%
Gas	--	15%	14%
Nuclear	--	3%	5%
Hydro	2%	2%	--
Other (purchases)	--	10%	8%

* Source: 1977 Annual Reports, all three utilities.

In compliance with an order by the PUC, PP&L filed tariff changes in 1978 to switch from a fuel adjustment charge to a net energy cost charge. The main difference between the two was that the old fuel adjustment only included the cost changes in fossil fuels burned to generate electricity; the new energy charge takes account of fossil and nuclear fuels plus the benefits of sales to (and the costs of purchases from) other utilities.

The Wind Turbine Generation (WTG) installation by the Pennsylvania Power and Light Co. (PP&L) at Harwood, Pennsylvania (see Figure 2-1) is described by them as "an energy research project expected to produce more data than electrical energy". A primary motivation for carrying out this demonstration type project was that several customers were installing wind machines and requested, and were granted, permission to interconnect these systems to the PP&L distribution lines.

The equipment for two private systems was being supplied by a local company, Energy Development Company, Hamburg, Pennsylvania. These windmill generator units were rated at 225 kW and 45 kW. It was a relatively natural choice for PP&L to select the 45-kW wind turbine unit of the same manufacturer for the primary power source. In contrast with the private party installations, however, a three-phase connection to the utility grid is being used.

The overall project objective could be stated simply: to obtain operating experience. Three areas of very great interest were 1) the generation capability and time capacity of a wind powered system; 2) safety of the interconnection under all operating conditions; and 3) interaction with the system that could cause difficulties particularly with other customers. After an initial manned start up, a minimum period of 2 years of unattended operation is scheduled. An extensive set of tests is planned for this period.

2. System Information

a. System Description. From a power flow point-of-view the system has three elements: 1) the generation subsystem consisting of a wind turbine, a gear box, a generator (3-phase alternator), tower, and yaw positioning equipment; 2) the storage subsystem consisting of rectifiers and battery; and 3) the output subsystem consisting of a line commutated DC to AC inverter connected through transformers to a three-phase, 12-kV utility line. Overlaid over these power items are control, monitoring, status and annunciation, and metering functions.

The wind turbine blades are of the high-lift airfoil shape and aircraft type construction, consisting of stretching and riveting aluminum sheet around full length internal spars (see Figure 2-2). The weight is reduced from solid construction and the flexibility is felt to provide protection against wind gust loads and fatigue cracking. Blade length is 22 ft with the hub located at a height of 40 ft from the ground. Because of the low average wind speed a four-blade

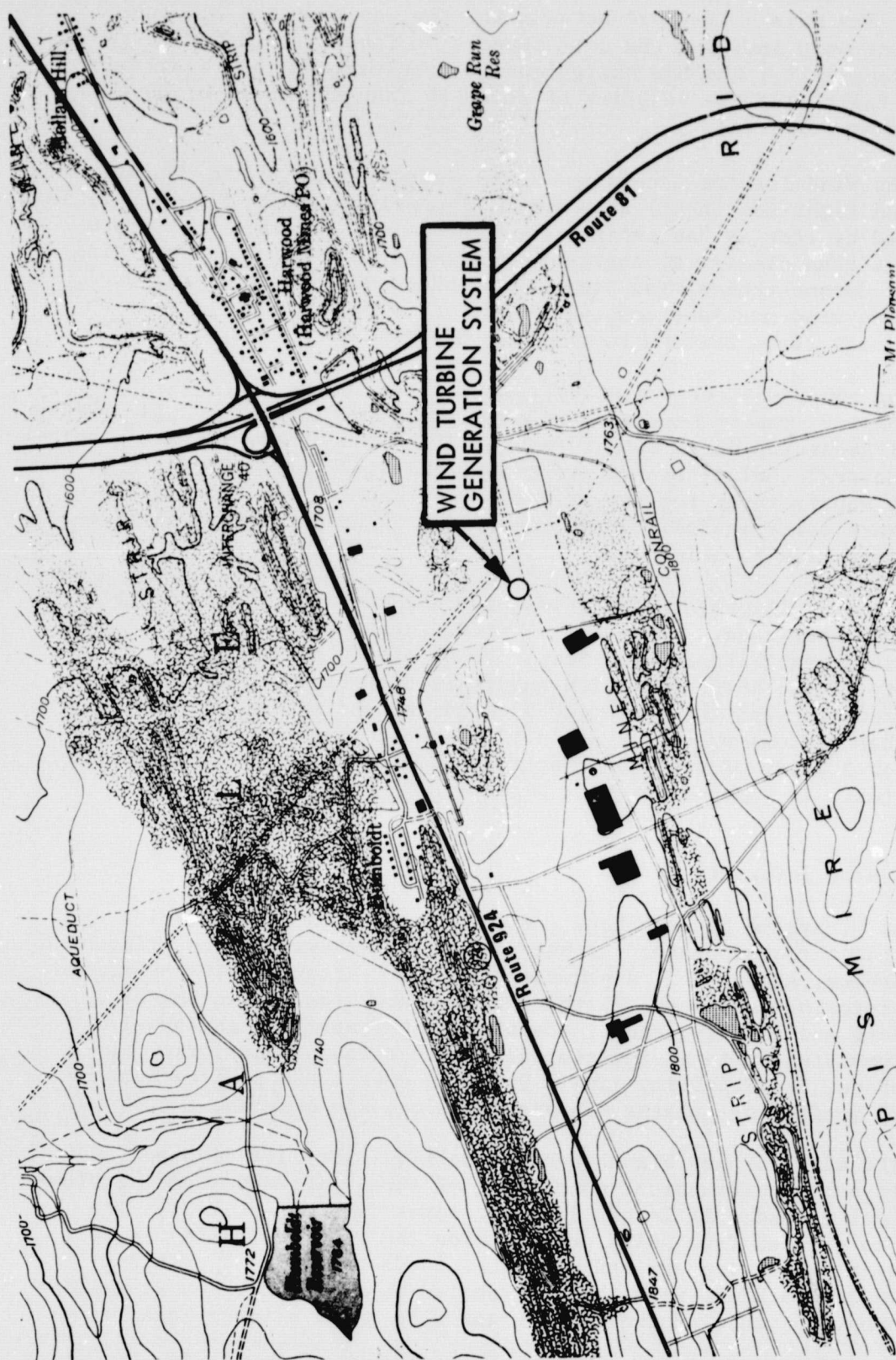


Figure 2-1. Geographical Location of the Wind Turbine Generation System (PP&L Service Territory)

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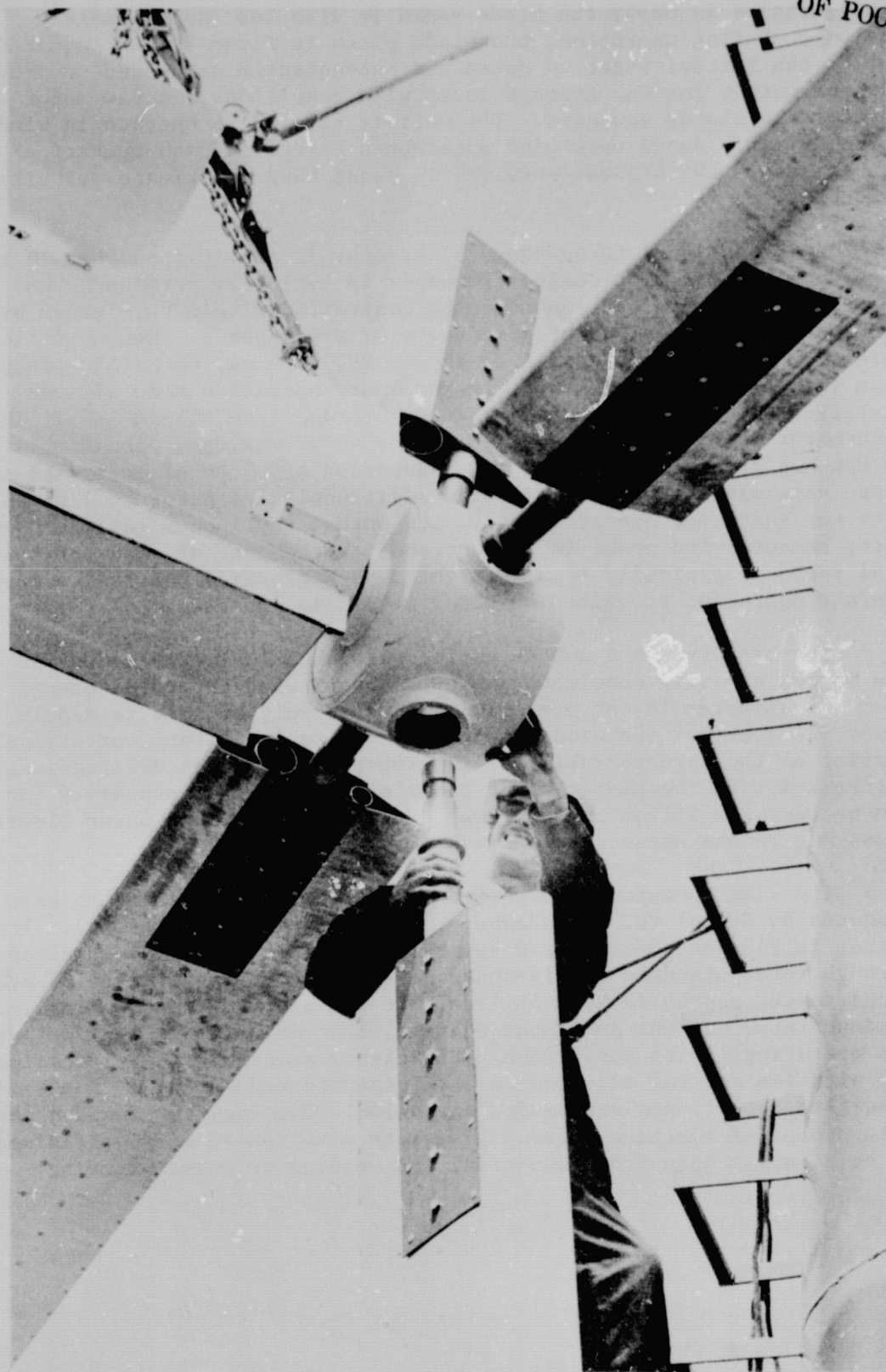


Figure 2-2. Wind Turbine Blade and Hub Detail (Courtesy of PP&L)

configuration is used; the blade speed is also low (approximately 36 rpm). During operation, the blade pitch is fixed but is adjusted during the initial start up phase and subsequently as needed to provide maximum output for the average local wind conditions. A yaw motor locates the blades downwind. The unit is allowed to operate in winds up to 35 mph. Above this wind speed both electrical and mechanical brakes secure the blades; survival in winds up to hurricane velocity is expected.

A conventional three-phase alternator is driven through a 30 to 1 step up gear box. The output frequency is typically between 30 and 40 Hz. System rotation speed can be controlled within this range by load variation for at least some range of wind speeds. Demonstration of direct synchronous connection to the 12 kV, 3-phase, 60 Hz line is planned as a future activity, however, the ordinary operating mode will be rectification and intermediate battery storage (see Figure 2-3). The alternator is rated 25 kW continuous and 45 kW maximum; wind speeds of 30 mph and greater needed for the generation of 45 kW of power and these same winds should provide the additional alternator cooling necessary for sustained operation above the normal continuous rating. However, because wind power is proportional to the cube of wind speed and wind speed is typically less than the 30 mph required for full output, average operation at quite low power level, is expected.

The battery has a 500 Ah rating with a nominal voltage of 180 Vdc. Its 90 kWh capacity should be ample to absorb wind generated energy when the inverter is not operating and conversely be able to supply power in excess of the wind generated level to facilitate operational testing of the inverter-utility line interconnection as desired (see Figure 2-4). In the simple power transfer mode - wind to utility line - the battery stabilizes the voltage levels and can smooth power fluctuations due to the usual unsteadiness of wind velocity.

The line commutated synchronous inverter is a Gemini S.I. unit produced by Gemini Co. of Cadanbury, Wisconsin (see Figure 2-5). Its output is 240 Vac, 3-phase, 50 kW at 250 Vdc input. It is connected through three standard single-phase distribution transformers (25 kVA each) to the nearby 12 kV PP&L line. It has minimum input voltage, maximum input current and input current slope adjustments that define its operating limits and region. Efficiency as high as 94% is claimed and with its several adjustments and automatic regulation it lends itself to the planned unattended operation. The inverter draws a certain amount of reactive power. Disturbance to the AC line is claimed to be no worse than from industrial arc welding or motor starting.

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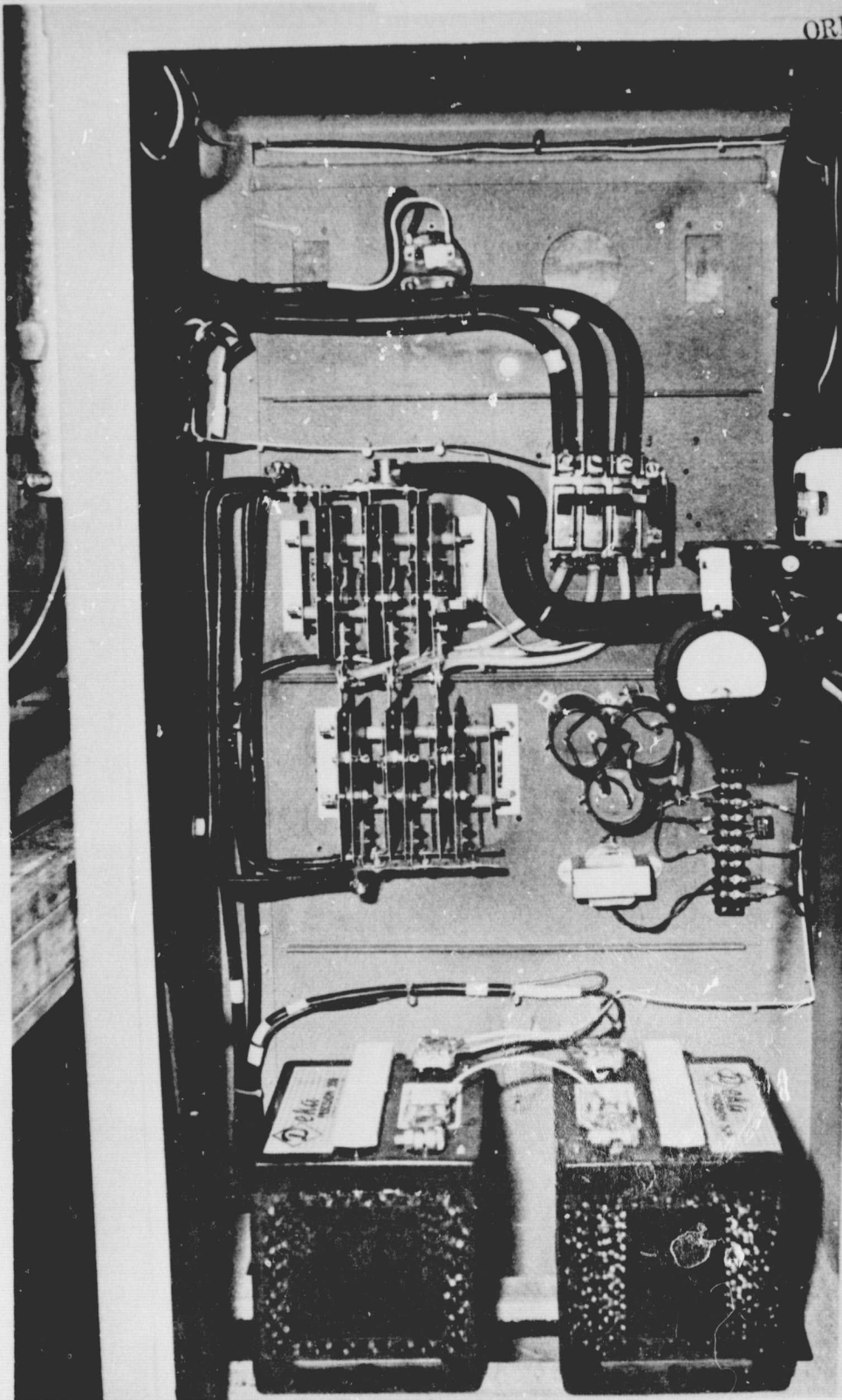


Figure 2-3. Inside View of the Rectifier Cabinet (Batteries provide back-up power to the WTG brake) -
(Courtesy of PP&L)

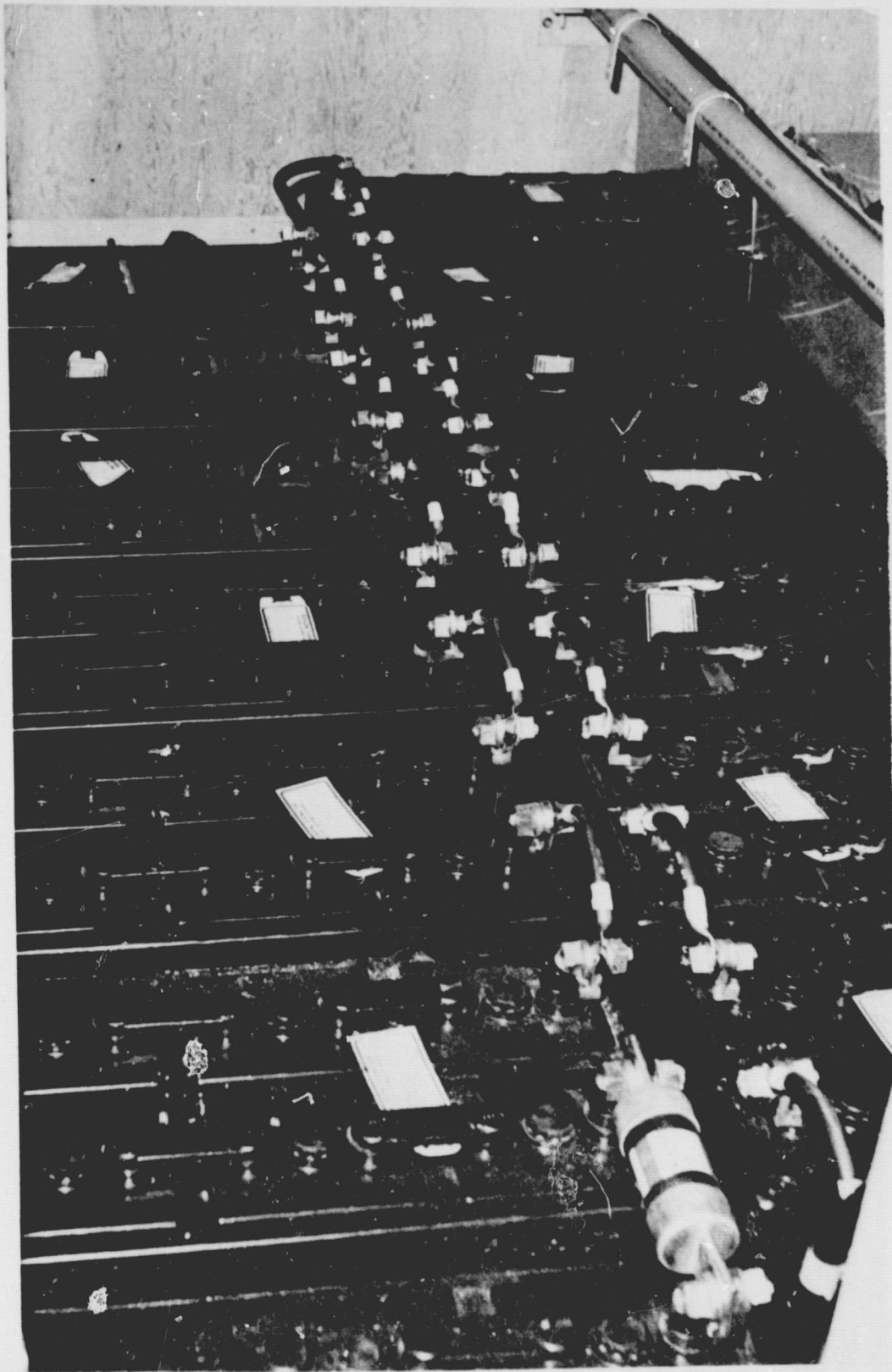


Figure 2-4. 500 Ah Batteries for WTG System (Courtesy of PP&L)

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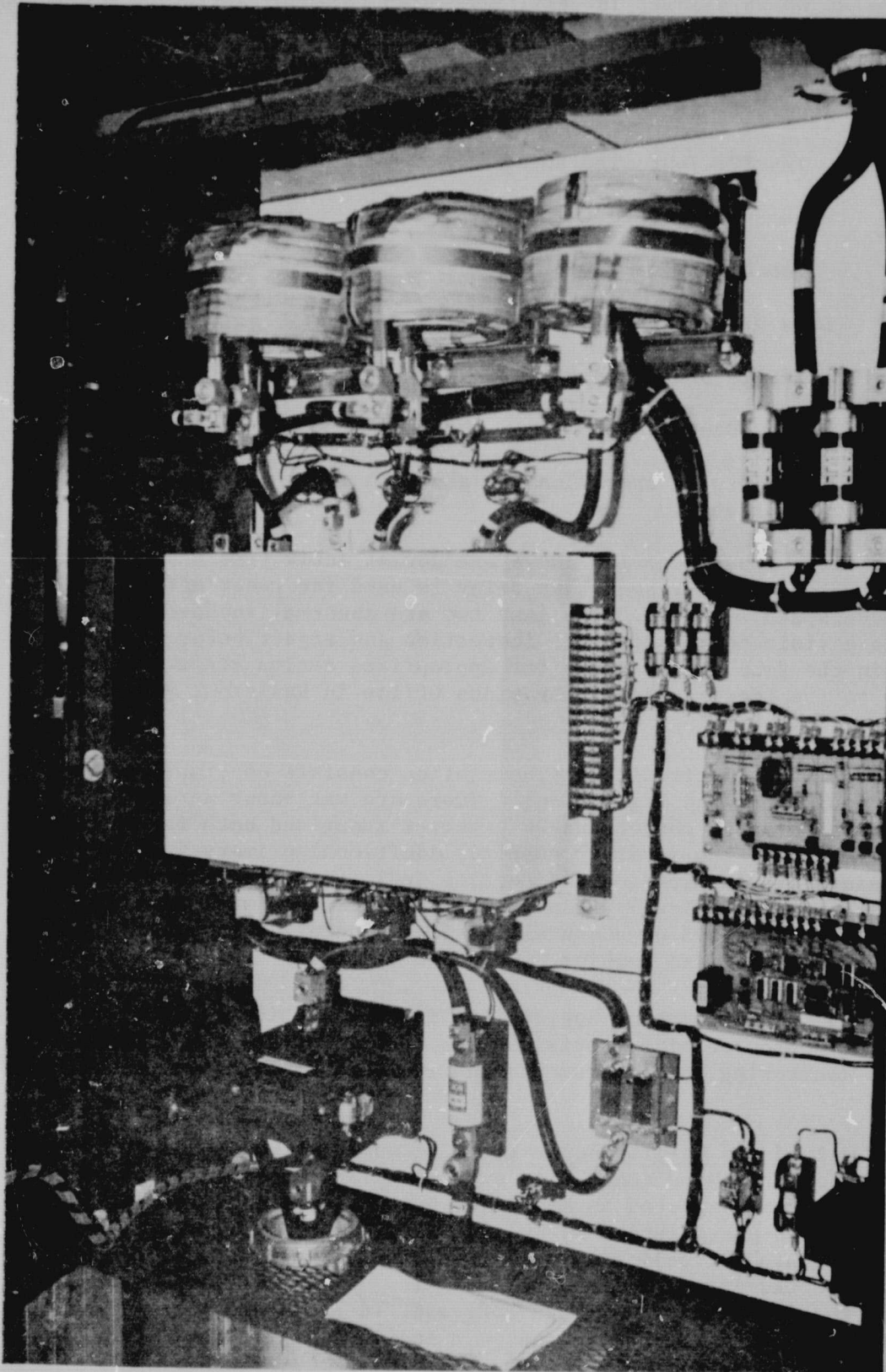


Figure 2-5. Inside View of Gemini Line Synchronous Inverter (Courtesy of PP&L)

A sizeable amount of control and monitoring capability is included in the system which allows, in part, scheduled unmanned operation - one of the demonstration goals. A local annunciator panel provides status indication in four categories:

(1) Inverter Off

Insufficient wind speed

(2) Wind Speed Shutdown

Too high wind speed

(3) Loss of Station Services

Single phase input line

(4) Safety Shutdown

Variety of operationally abnormal items are sensed and indicated.

The first two categories above are normal activities and are automatically reset - a four hour time delay is used for reset after wind turbine overspeed shutdown. The last two are abnormal incidents requiring a visit to the site for inspection and repair before restart. Changes in the four status items for appropriate action are transmitted by radio to the Local Systems Operations Office in Hazleton, PA, about four miles away.

The primary electrical instrumentation consists of standard PP&L metering equipment (see Figure 2-6). There are watt-hour meters at the AC turbine alternator output and DC inverter input and both watt-hour and VAR-hour meters at the inverter output. Additional primary instrumentation consists of wind speed and direction indicators. Data from all the above units are periodically recorded on magnetic tape with time tags; tapes will be processed on a monthly basis. Figure 2-7 shows a single-line diagram of the Wind Turbine Generation System.

During special testing appropriate instrumentation is provided. The control house contains provisions for both temporary and additional permanent monitoring and instrumentation equipment.

b. Load and Utility Connection Characteristics. The utility connection for this wind generation system appears to be quite different from what might be expected in a private party situation. The connection is three-phase into a 12 kV line originating at a sizeable substation less than one half mile away (see Figure 2-8). Even if 50 kW of power is injected into the line from the wind driven unit, the overall effect on the line is minimal. In contrast, in a private party installation the wind unit might be located on a small, single phase, distribution lateral.

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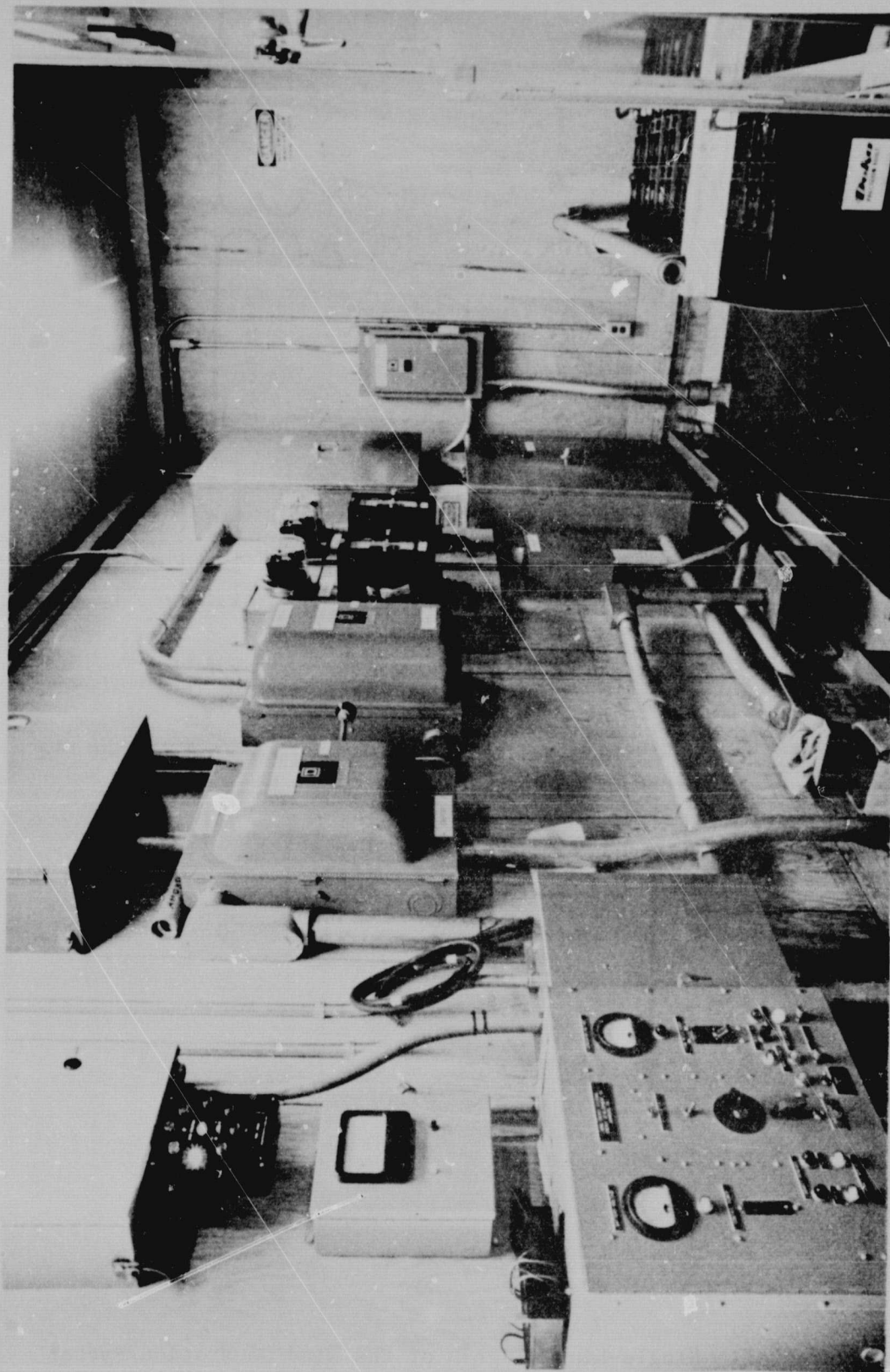


Figure 2-6. View (Front to Rear) WTG Control Panel, Inverter Switching, Station Metering and Recording Equipment, and Station Isolation (Courtesy of PP&L)

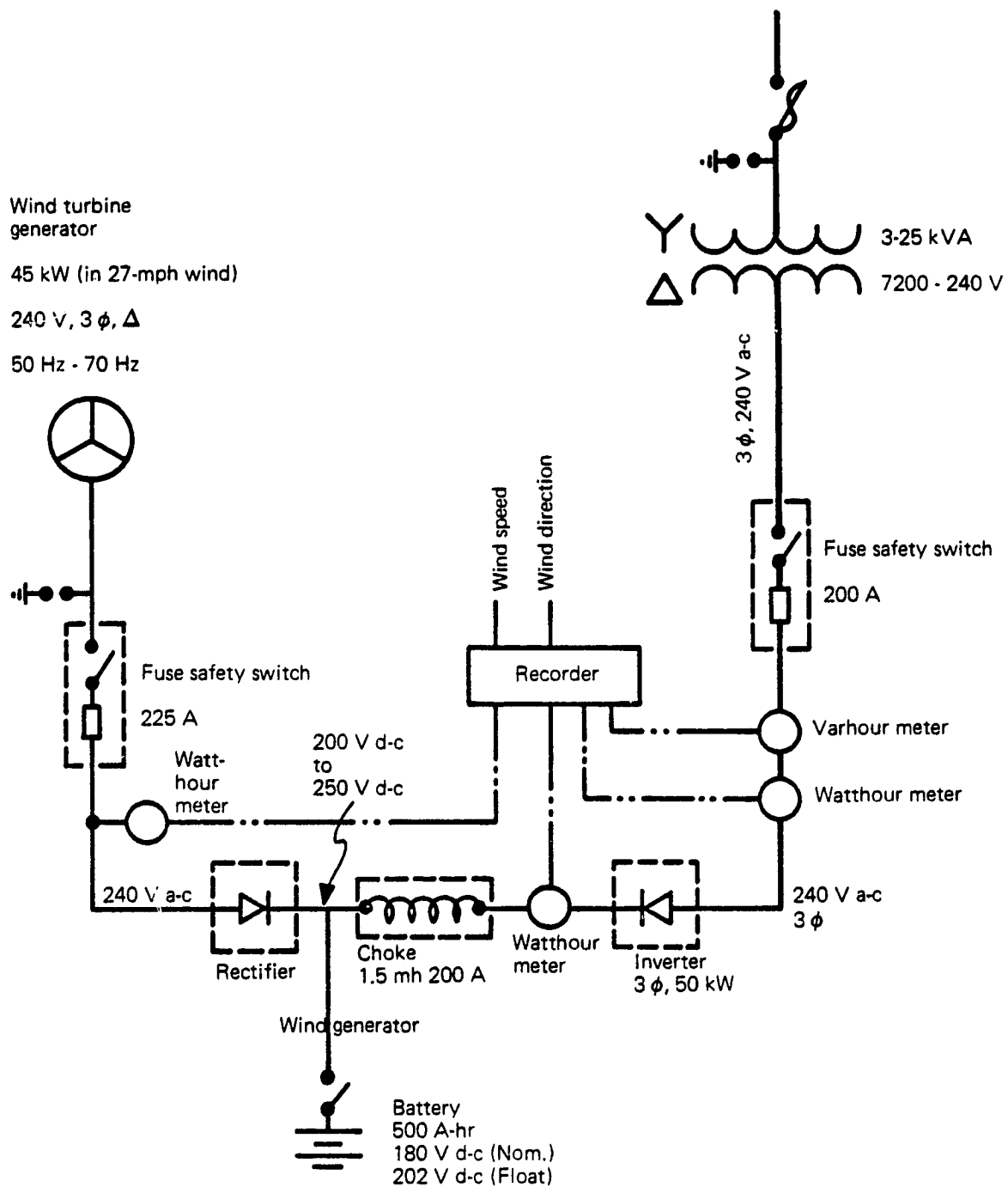


Figure 2-7. Single-Line Diagram of the Wind Generation System
(Source: Power Engineering, July 1979)

c. Site. The installation is at about 1800-ft elevation on a plateau atop a mountain range at the location of a former generating station. The immediate surrounding area was cleared of trees and brush. The equipment site itself is fenced, a ground wire grid installed, and the enclosed area graveled. Access is controlled by a locked gate and the installation has been equipped with the required electrical and mechanical capabilities and safety precautions.

The fenced site (shown in Figure 2-9) is 125 feet (N-S) by 100 feet (E-W) with the windmill located in the north end. A 12-ft x 12-ft prefabricated building located in the south end is the control house.

d. Construction and Installation. The decision to proceed with the wind turbine project was made in November 1977. The initial plans allowed about 6 months for construction with system checkout to begin June 15, 1978. PP&L personnel performed the engineering and construction tasks. Because of bad weather and other priorities the construction was not completed until September 1978.

The purchase cost of the wind turbine - alternator - rectifier - inverter package from Energy Development Corp. was about \$35,000. This included engineering support associated with installing the windmill and the 100 hours of manned startup operations. The batteries cost about \$5,000. The costs associated with the site preparation described above were estimated at \$200,000.

e. Operations. Startup and initial manned operation began October 12, 1978 and were concluded in May 1979. Operating periods were intermittent and individually short on fewer than 40 days out of a possible 200 with an average duration of about 3 hours. This type of operation was deliberate; a major objective was a final adjustment of the windmill blade pitch angle to best match prevailing average wind conditions. About 90 hours of data were taken at 30 different times from which the average wind speed was determined to be about 11 mph. There was one over-wind-speed situation: 7 hours when the average wind speed was at or above 20 mph, and about 16 hours with average wind speed between 15 and 20 mph. During this time about 170 kWh of energy was inverted to AC and passed into the utility line while about 340 kVARh of reactive load was drawn from the line; the average rates were about 1.7 kW and 3.4 kVAR respectively.

f. Observation. In contrast with the next two study cases, this wind generation project is truly an experimental effort. If the winds prevailing during the 100 hours of tune-up of the propeller pitch angle are representative, more data than power will surely be generated. This is not at all necessarily bad; the installation is really an excellent test bed for a wide range of experiments that could simulate a full range of practical situations. Under utility sponsorship, the full range of PP&L resources in both manpower and equipment can be temporarily loaned to the project to carry out specific tests and experiments.

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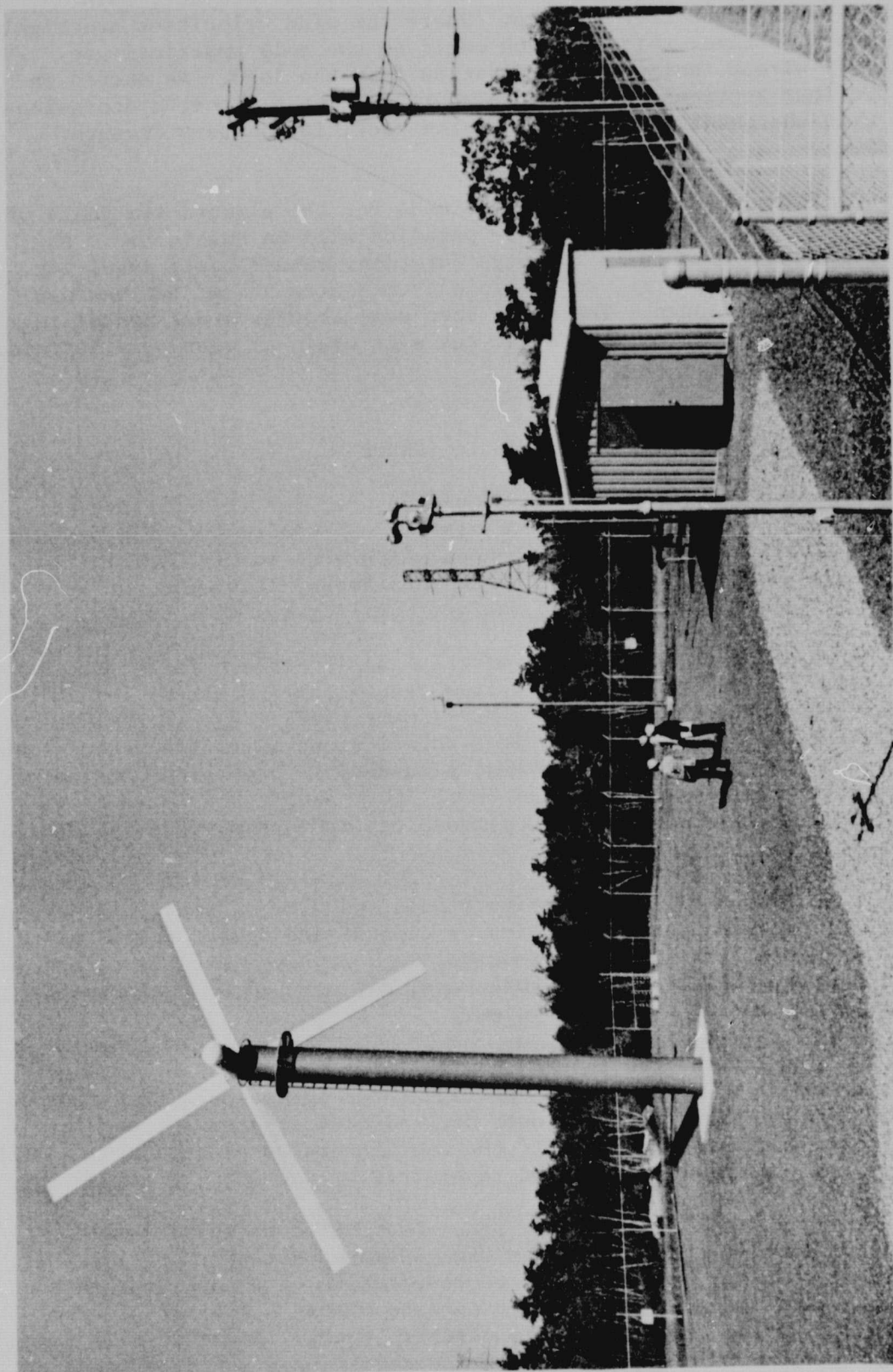


Figure 2-9. PP&L Harwood 45-kW WTG System Site (Courtesy of PP&L)

In contrast, this time with the photovoltaic project, this installation has battery storage. Where the wind velocities are highly variable with time, this approach could be the only practical one. It does very nicely isolate the generation from the load. As stated in the previous sections, PP&L does plan to attempt a direct synchronization with the power line, bypassing the rectifier-battery inverter equipment.

Extensive test plans have been made for the planned two years of operation. Most of the time, the operation will be unattended. At times, probably only for a few days duration, manual tests involving such things as waveforms, and efficiency measurements of the various components are planned. There has been some thought about installing a solar photovoltaic cell array at the site again as part of a learning experience for the PP&L.

3. Financial Analysis and Economic Issues

The analysis which follows should be used for illustrative purposes, rather than to judge the feasibility of wind generating systems. This WTG was built by PP&L for reasons which were mostly experimental. Because the system was designed as an experiment, it should not be expected to operate at a profit, as most utility investments do.

An economic measure of the worth of an investment is Net Present Value (NPV). A generation system is a beneficial investment for a utility or individual user if its NPV is positive, i.e., if the discounted fuel and electricity savings outweigh the initial investment and additional O&M expenses. If several alternatives are being considered, the one with the highest NPV will be the most profitable option. (A more complete explanation of NPV methodology and assumptions is contained to Appendix A.)

In an Edison Electric Institute questionnaire on small wind systems, PP&L provided the information on capital and operating costs listed in Table 2-2. This information, when combined with operating data and some general economic forecasts, may be used to estimate the net present value of the wind system.

Table 2-2 lists the initial capital cost and annual operating expenses for the WTG system. Offsetting these costs would be a reduced need to purchase power (if the user buys electricity) or a reduction in needs for additional capacity (if the user generates electricity). Each of these situations is considered separately.

During initial tests of the WTG, about 90 hours of data were taken, and about 170 kWh of energy was generated during this time. If these test data may be considered representative of annual weather and operating conditions, the WTG would produce about 16,550 kWh of electricity during the year. How this electric energy is valued will depend critically upon who the user is. An industrial user would be reducing

Table 2-2. Costs for WTG (Approximate)

Equipment, Instruments, and Materials		\$ 34,500
1) WTG, AC-DC Rectifier, and Controls	\$15,000	
2) Battery	4,500	
3) Inverter with Choke	10,000	
4) Instrumentation and Recording Equipment	5,000	
Installation of Equipment		15,000
Site Preparation, Building, Fences		<u>200,000</u>
Approximate Capital Costs		\$249,500
Approximate Annual O&M Costs	\$1,500 - \$2,000	

purchases from a utility and industrial rates averaged about 3.6 cents/kWh in 1978. However, a utility such as PP&L would be able to reduce its purchases from other utility sources: in 1978, PP&L was paying approximately 2.15 cents/kWh for electricity received from the Pennsylvania-New Jersey-Maryland (PJM) interconnection.* Thus, industrial users valuing each kWh at 3.6 cents would see \$596 in 1978 electricity savings, while PP&L might value the same output at \$356. In either case, the WTG system built for PP&L usage is not an economically attractive alternative to purchased power: annual electricity savings do not even cover the annual O&M costs, let alone the initial investment. Table 2-3 shows this in greater detail: both utility and industrial owners would lose money by investing in this WTG, as shown by the negative NPV. Annual electricity savings of \$15,323/yr (in current dollars) would be needed to make the NPV zero, and the investment break even. But the extrapolation of output levels generated results in an electricity rate of 93¢/kWh, which is excessive by today's standards.

The analysis above is based on data from PP&L along with some general economics assumptions. It may be imprudent to generalize, because some of the circumstances were specific to this installation. The wind speed in the sample data may have been below average, so that annual output is higher than 16,550 kWh. The capital cost of other WTGs may be less if batteries or testing equipment is not included or if site preparation costs are less. O&M costs for this system may be high, because large amounts of testing are done on this WTG. Reductions in the capital and recurring costs, or additions to the annual electricity output, would contribute to the economic viability of wind power. Net output would be higher if WTG was directly connected and thus will affect the cost.

*Source: Pennsylvania Power and Light Company, Profile: 1968 - 1978.

Table 2-3. NPV Calculations for WTG*

		ASSUMPTIONS	
NPV Symbol (see App. B)	Variable	Case 1: Utility Ownership	Case 2: Industrial Ownership
K	Capital Cost, \$1000	249.5	249.5
C _{O&M}	O&M Cost, \$1000	1.5	1.5
R _j	Value of Electricity generated/saved, \$1000	0.4	0.6
	Escalation Rates, %		
E _{O&M}	O&M	7.8	7.8
E _j	Electricity	8.2	8.2
N _s	System Life, yrs.	20	20
N _a	Accounting Life, yrs.	10	10
r	Discount Rate, %	15	15
t _i	Income Tax Rate, %	50	50
t _m	Misc. Expense Rate, %	2.5	2.5
t _c	Investment Tax Credit, %	10	10
Formula for NPV*: NPV = R _j (11.2095) - C _{O&M} (10.8635) - K (0.623107)			
Net Present Value, \$1000		-167.3	-165.0

As an example, if a potential user already has a suitable site and does not use the dc approach this might eliminate most of the site preparation needs** (\$200,000), dc conversion equipment (\$14500), and test instruments (\$5000). The capital cost becomes approximately \$60,000. In this case, the WTG must save the user \$4789/yr (in 1978 dollars) to break even. For an approximate 20,000 kWh/yr, of output, this implies an electricity rate of 24 cents/kWh; while this rate is still high by current standards, it is not as unprofitable as the previous cases.

* See Appendix A for calculation detail.

**Still there is a need to provide foundation, grounding, conduit, disconnect switch, etc. (here assumed to be \$30,000).

There are a number of other factors which also affect economic viability of wind systems. One of these is the buy-back rate for electricity. If a utility customer plans to own a WTG and generate more power than consumed, the rate received for that excess power will determine how large a WTG is to be built as well as how profitable the system will be.

Although the procedure is not meant to establish a precedent, PP&L has arranged to pay for WTG energy at the rate of PP&L's average fossil fuel cost for the twelve months ending December of the year purchases are made.* For 1978, the fuel cost information was:**

<u>Fuel Source</u>	<u>Cost (c/kWh)</u>	<u>% of Total</u>
Home Heating Oil	4.10	0.4
Crude and Residual Oil	2.23	20.9
Coal	1.26	78.7

This results in a buy-back rate of 1.474 cents/kWh. This rate is below the new contract cost of fuel to utilities and (in contrast to the SCE case) it does not include a component which represents the savings in capacity additions such a system makes possible.

The financial analysis undertaken above confirms the PP&L statement earlier in this report — that PP&L has installed this WTG for informational reasons rather than financial ones. A number of factors — initial cost, average wind velocity, buy-back rates, and operating costs of alternatives — will influence the decision to invest in WTG systems, and can be accounted for in the NPV framework. But the prime economic motivation for this WTG seemed to be long-run — assessing the cost of interfacing with a wind system, and development of contractual guidelines and requirements for future WTG systems — rather than increasing the performance or profitability of the current system.

4. Institutional and Environmental Issues

A number of diverse problems are considered in this subsection. Each one — capacity problems, safety issues, licensing procedures, and resource availability — is discussed in turn below.

a. Capacity Problems. PP&L has found itself in a vulnerable position during the energy and environmental upheavals of the past decade. Originally dependent upon coal and hydropower, PP&L diversified into oil-fired capacity as its sources of new hydropower diminished and increasingly stringent environmental regulations were placed upon coal.

*Source: Agreement between PP&L and Peter D. Fuller, February 1979.

**Source: PP&L, Profile 1968 - 1978.

When oil supplies became less secure, the utility again tried to diversify, this time into nuclear power; but nuclear generation has encountered public opposition. A review of PP&L's capacity situation shows that it is highly vulnerable to an oil shortage. During the 1978-79 winter peak, the company had a 39% reserve margin; but without oil, this reserve margin suddenly becomes negative 7%.* This suggests that PP&L is interested in supplementing and diversifying its present capacity; it has expressed an interest in exploring cogeneration,* and it is currently analyzing the prospects for other wind systems.

b. Safety Issues. A number of potential safety hazards exist in any industrial installation. To ensure the safety of maintenance personnel and the surrounding community, the following steps (many of which are standard operating procedures in the industry) were taken by PP&L:**

- (1) The site is enclosed by a 100 ft x 125 ft chain link fence.
- (2) All doors and gates at the site contain a standard PP&L key-and-lock system.
- (3) All structures are grounded.
- (4) A minimum 150 ft clearance is kept between the WTG and all transmission and distribution lines and other structures.
- (5) The wind turbine tower includes safety climbing provisions.
- (6) A braking system was installed to lock the turbine into a stopped position for wind speeds exceeding 35 mph.
- (7) The design of the WTG, tower, base, and foundation were reviewed by PP&L personnel.

In addition, PP&L requires a review of privately owned WTG interconnections with the PP&L system and to include equipment which allows disconnection at the incoming service.

c. Licensing Procedures. When installing the WTG, PP&L indicated that the state regulatory commission did not become involved with the project. If a WTG is installed, a local zoning board review may be necessary. The PP&L wind system had to conform to a number of local building and safety codes, but these did not delay the installation. Environmental impacts of the system were considered minimal, and mostly visual; because of the visual impact, esthetics were considered in the design.

*Source: PP&L, Profile 1968 - 1978.

**Source: J. A. Miller and J. E. Pfluger, "PP&L Wind Energy Research Project," ER-294019, Report No. E-62-R, March 29, 1978.

d. Resource Availability. Initially, the site upon which the WTG was placed (a former generating station) was considered by PP&L to have sufficient wind for generation purposes. However, operational experience seems to indicate that weather conditions were not as favorable as predicted. An optimized WTG installation would require a better matching of turbine design to prevailing wind conditions.

B. PHOTOVOLTAICS

1. Introduction

When the 60 kW PV system selected for this study was initially tested at the Delta Electronic Control Corporation's (DECC) facility in Irvine, California, it was connected to the Southern California Edison Company (SCE) system. After the PV system was moved to its permanent Mt. Laguna location, it was no longer connected to the SCE system. In this case it is connected to the isolated power system located at the Mt. Laguna AFB. This is a diesel powered power system which is operated by the Air Force base personnel. We will analyze the impact of the PV system on both the SCE and Mt. Laguna systems.

SCE provides electricity to a major portion of Central and Southern California. In 1978 the resources used for power generation consisted of 93% oil, 18% gas, 10% coal, 9% hydro, 17% purchased and 3% nuclear. Nuclear power comes from the San Onofre Generating Station; SCE receives 80% of total output, and San Diego Gas and Electric (SDG&E) obtains the remaining 20%.

To facilitate load management and the introduction of new energy technologies, SCE has established time-of-use rates and experimental tariffs for interruptible service and parallel generation. All large industrial customers on the Edison system are now on time-of-use rates, and tests are under way with other industrial, commercial, and residential users.

Experimental Schedule No. D-PG applies to domestic customers who will derive some or all of their electrical requirements from energy sources connected for parallel operation with the utility. These sources may include (but are not limited to) windmills, water wheels, solar conversion, tidal action, and geothermal devices. This rate schedule follows a decreasing-block-price format: there is a minimum monthly charge of \$6.55 per month, with the first 100 kWh of net energy (energy supplied by the company less energy generated by the customer) provided at no additional charge; the next 200 kWh are supplied at 3.562 cents/kWh, and all additional electricity is supplied at 2.332 cents/kWh. Schedule No. TOU-8-1 provides rate reductions for large customers willing to defer portions of their electricity use during periods of peak demand. Net billing is reduced by \$2.00 per kW per month for each kW of utility-controlled interruptible load, and by \$1.75 for each kW of customer-controlled interruptible load. These new rate schedules focus on incorporating new technologies into the utility system, and on sharing the heavy summer peak demand which SCE has.

Mount Laguna Air Force Station is a remote site 60 miles east of San Diego, located atop a 6,000 foot peak in Cleveland National Forest (see Figure 2-10 and 2-11). Approximately 200 civilian, military, and Federal Aviation Administration personnel operate the station and the radar installations. These radar facilities are scheduled to be turned over to the Federal Aviation Administration, and will be administered jointly by the FAA and the air defense system for air traffic control and surveillance.

All electricity is produced at the station by diesel powered plant consisting of seven generators. Six generators are rated at 300 kW, and one diesel generator is rated at 250 kW. Three generators run continuously for 24 hours per day, seven days per week. The monthly usage of electricity — about 500,000 kWh, with an average load of 750 kW — is met by burning 38,000-40,000 gallons of diesel fuel (11-12 kWh/gallon diesel fuel). Diesel fuel is purchased in 75,000 gallon lots, for about 73¢/gallon. There is also a 150,000 gallon storage capacity.

The Mt. Laguna Solar Cell Power Augmentation Project is one of the projects of the joint Department of Defense and Department of Energy Military Applications of Photovoltaic Systems program. The U.S. Army Mobility Equipment Research and Development Command (MERADCOM) has program management responsibility for these applications which are sponsored by DOE. There are two major parts to the Mt. Laguna installation; 1) the solar cells themselves and 2) the installation, cell power gathering and monitoring and ultimate inversion of the power from DC to AC for transfer to the diesel driven power system. The solar cells were procured under contracts managed by the Jet Propulsion Laboratory as part of the Low-Cost Silicon Solar Array Program sponsored by DOE. The control and monitoring equipment and the inverter were supplied by Delta Electric Control Corporation (DECC) located in Irvine, California.

The primary objective of the project is large-scale hardware demonstration. MERADCOM has managed several current military application demonstration projects starting in 1976 at power levels in the range of 100 watts and in 1977 at the 8 to 10 kW level. This current project, which is now on line, is rated at 60 kW. The smaller earlier applications were often for a single, specific application such as small battery chargers and remote radio relays. In contrast this photovoltaic system is connected to what in fact is a utility type power system.

During daylight hours the solar cell system is expected to supply up to 10% of the average load, displacing diesel driven power sources. The overall system thus is really a very good example of a "Dispersed Source" supplying a reasonable amount of energy into a power grid. In addition during construction and test of the inverter and other parts of the installation at the DECC plant in Irvine, California, the solar system was connected to the Southern California Edison utility grid. Only 30 kW of the solar cell array was available; at this level, power was delivered into the utility grid with no difficulties.

At the time of the site visit to Mt. Laguna, no particular problems with solar cells had yet occurred. Subsequent cell failures occurred well after these case studies were under preparation.

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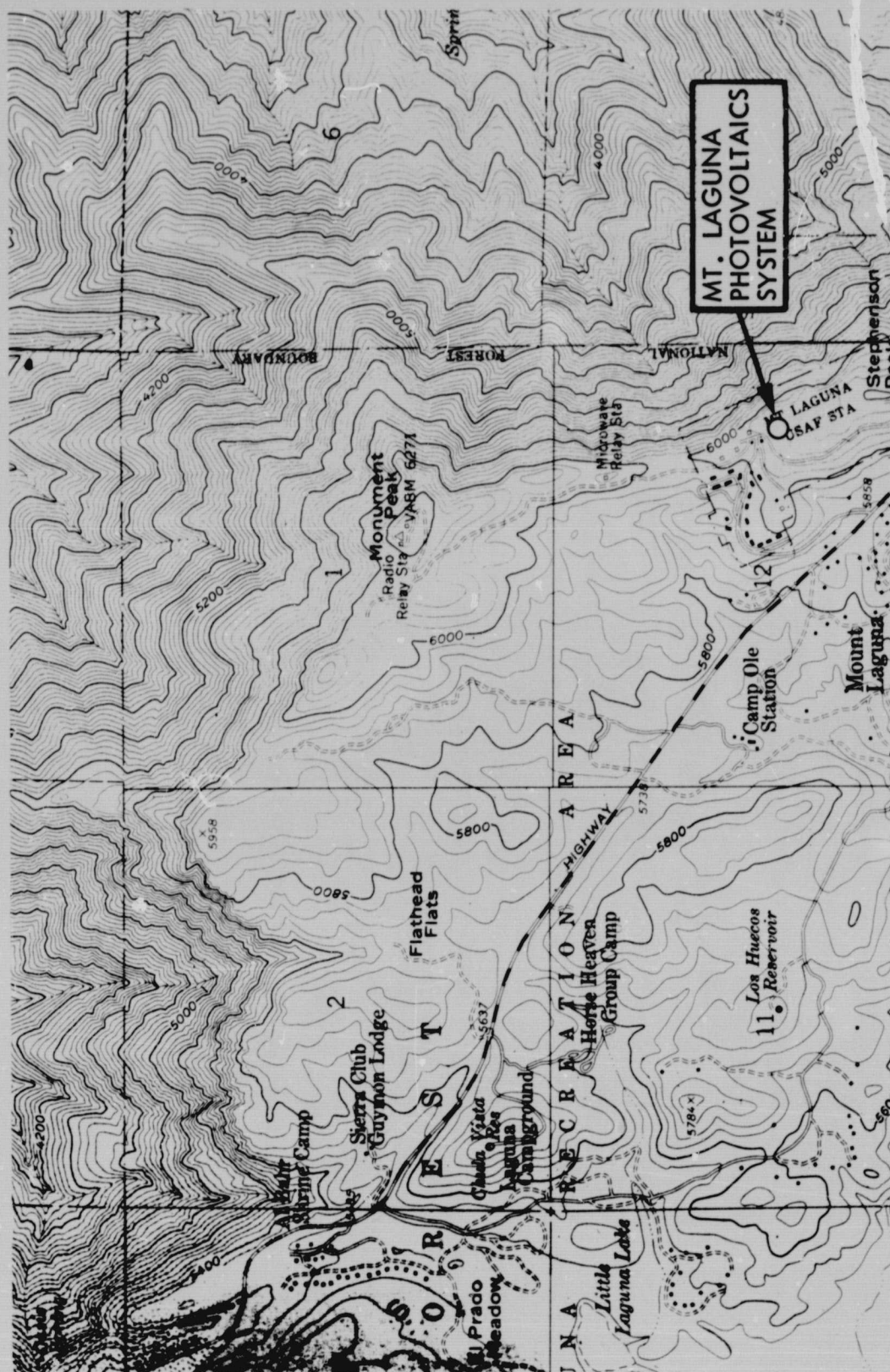


Figure 2-10. Geographical Location of the Mount Laguna Photovoltaics System

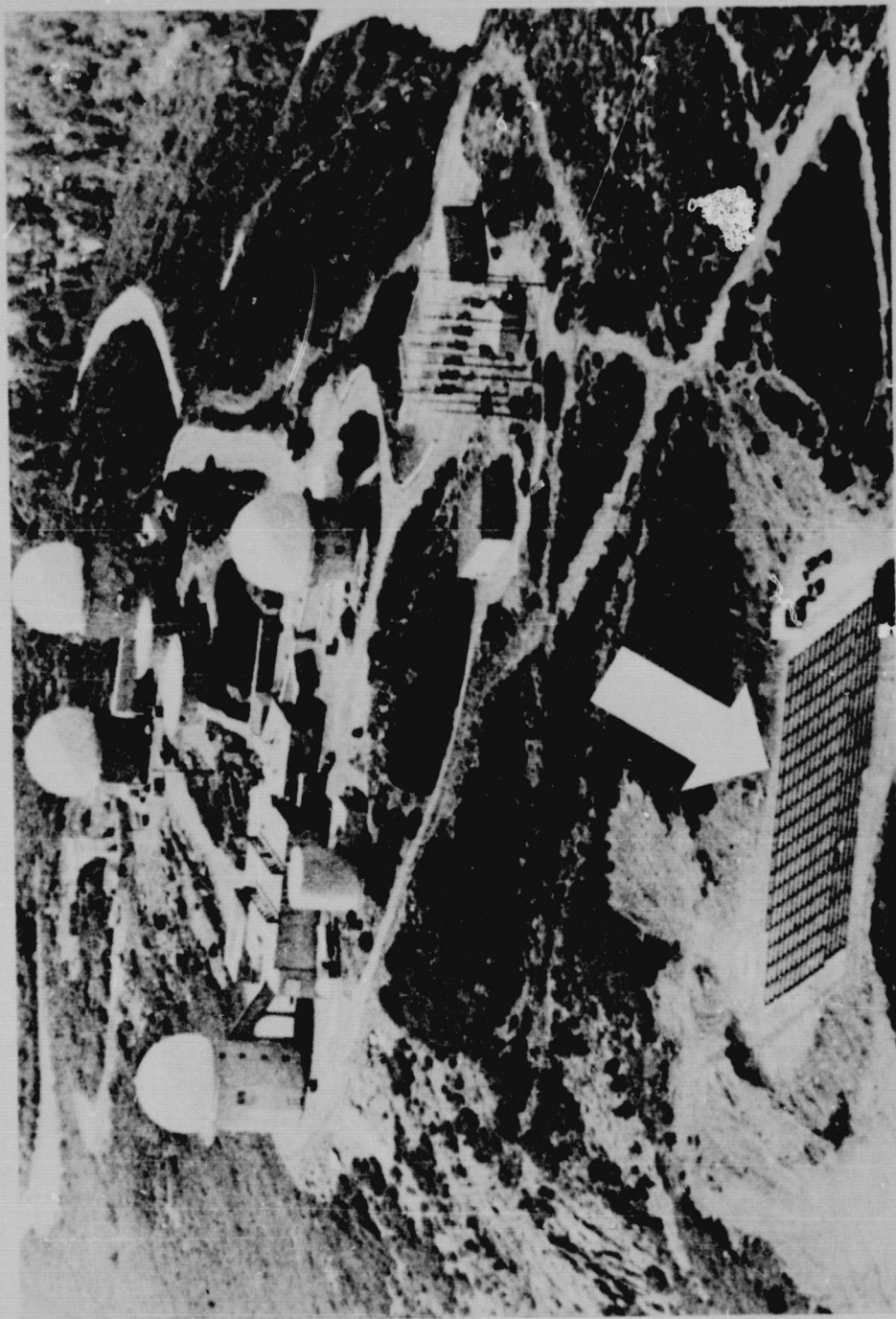


Figure 2-11. Location of Photovoltaics System Site at Mount Laguna Air Force Station
(Courtesy of Mt. Laguna AFB)

A distinct feature of this system is that no batteries are used. Power developed by the solar array is fed to the power grid on an instantaneous basis and under maximum power transfer conditions.

2. System Information

a. System Description. There are 2366 solar cell modules in the full array. About 68% of these were built by Solar Power with 40 cells per module and the remaining by Solarex using 42 cells per module. In both cases 14 modules are connected in series to form 169 strings. The design voltage for the string is 230 Vdc; each string delivers its current to positive and negative bus bars in the control house through a fuse, diode and selector switch in the positive side and a small resistor for individual current measurement in the negative side. The approximate dimensions of a Solar Power module are 46 in. x 15 in. and the Solarex are 23 in. x 23 in. There are spaces between the individual cells. The cells are circular in shape. The total area of the 2366 modules is about 10492 square ft or about 1/3 acre.

The voltage of each string is 230 V at rated current and normal operating cell temperature. The positive and negative leads from each string are brought separately to the Paralleling and Monitoring Panel. This panel is about 3 ft wide by 6 ft high. At this panel, an individual string can be disconnected from the power processor and may be loaded and monitored individually.

The power processor consists of: 1) a DC voltage limiter, 2) a self-commutated inverter and, 3) controller (control logic). The controller performs 4 major functions:

- (1) Peak power tracking, i.e., to maximize the instantaneous power obtained from the array.
- (2) Monitoring of system parameters. This includes metering of both real and reactive power, and measurements of various voltages and currents.
- (3) Automatic shutdown and start-up (e.g., automatic start-up when power exceeds 6 kW, and automatic shutdown when it goes below 6 kW on a persisting basis), and protection.
- (4) Minimization of reactive power.

The fuse protects the individual string, the diode isolates a bad string, i.e., shorted or low back-resistance, from the other operating strings and the switch connects the string to the common positive bus or to test circuits. In the test position, a condition of open circuit, short circuit and two intermediate load levels can be selected. Input metering is provided. Connection to the inverter is through a contactor in the positive lead. When this contactor is de-energized, a second pole of the contactor is utilized to short circuit the array. Output metering is on power conversion unit.

The inverter supplied by DECC is adapted from a 75 kVa design for an uninterruptible power supply. Basically it is a self-commutated 24 SCR bridge circuit producing a three-phase AC output. The lowest harmonic is the 11th. The inverter is connected through an impedance to the output of the diesel power plant. The inverter operates synchronized to the diesel plant; the inverter was observed to draw about 5 KVARs of reactive power while delivering 45 kW of real power to the system. Total harmonic distortion was specified at less than 3% and is obtained with minimal filtering. The DC to AC energy conversion efficiency is very good; it rises very rapidly from 50% at the lowest operating level of a few kW to 90% at 25 kW and peaks at 92% over the 40 to 75 kW range.

As stated previously, no batteries are used. Because of this and the characteristics of solar cells, the operation of the cell-inverter system is somewhat different than that typical of an uninterruptible power supply. Over its useful operating range, the solar cell can be viewed as a current source with a highly variable internal resistance which is a function of the current output. At low current, the cell acts like a fixed internal voltage source with a fixed and, in fact, relatively low, internal resistance (Figure 2-12). As the current is increased by reducing the external resistance more power is indeed delivered — at first. However, well before the maximum power transfer point for a fixed voltage-fixed internal resistance system, (load resistance equals internal resistance) the cell terminal voltage begins to drop increasing rapidly with relatively small increases in current. At very low external resistance load (near short circuit conditions) the voltage-current relationship approaches that of a true current source, i.e., a very high internal voltage source with very high internal resistance. Indeed solar cells are routinely short circuited and the resulting currents are not at all destructive. Between short circuit and open circuit operation (where in both cases there is no delivered power) there is, as must be, a maximum power point. For good, efficient, cells the point is generally located in a region bounded by 80 and 90% of the open circuit voltage and short circuit current. However, although the 80 to 90% boundaries are relatively fixed, the absolute value of open circuit voltage and short circuit current vary significantly with the insolation flux to the cell and the cell temperature.

b. Load and Local Connection Characteristics. During the testing phase, the PV system was connected to the SCE system. The output from the power processor was connected to DECC's main 480 V, 3-phase bus in parallel with the incoming feed from SCE. A conventional circuit breaker served both as protection and lockable disconnect for the photovoltaic system. In this case, SCE did not require sole control over the disconnect. Figure 2-13 is a single-line diagram showing the photovoltaics system connection.

The PV/inverter system connects to the power grid at 480 V 3-phase.

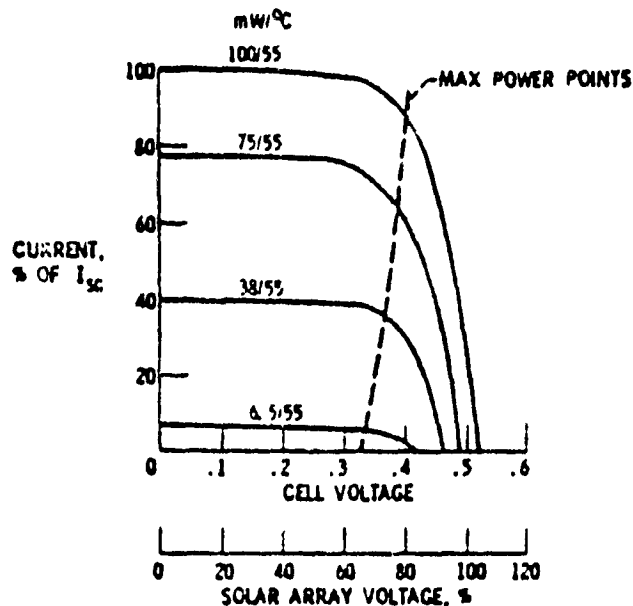


Figure 2-12. Solar Cell Typical Electrical Characteristics

c. Site. The PV system is located on a 170 ft x 190 ft site in the high ridge of a range of coastal mountains about 45 miles from the Pacific Ocean (see Figure 2-14). The array field was leveled and fenced although public access to the entire area is controlled since it is on a military base. The ground rises to the west so the array does not see a horizontal sunset. The ground to the east drops precipitously for several thousand feet and there is no obstruction to the morning sunlight. This last high ridge receives a considerable amount of rain and snow — typically 50 in. of snow per year, but sometimes as high as 120 in. The snow does not accumulate or remain at any depths except in rare cases. The cleaning action of the rain and snow on the tilted solar panels is one of the actions to be observed during the year round operation of the array.

d. Construction - Installation. The mounting frames for the cell modules are heavily galvanized steel tubing. These are carried on wood vertical supports which provide the tilt angle of 25° . These in turn are carried on small concrete footings. The installation is quite straightforward and designed to withstand 120-knot winds. Part of the array was temporarily installed at the DECC facility in Irvine which provided an opportunity to develop handling and installation techniques.

The power conditioning equipment is installed in a small concrete block house adjacent to the array. Fan ventilation is provided to circulate outside air; the inverter unit has an integral fan that circulates the inside air through it. Although the typical operation is unmanned, electric heaters were installed for winter comfort of personnel who monitor and observe.

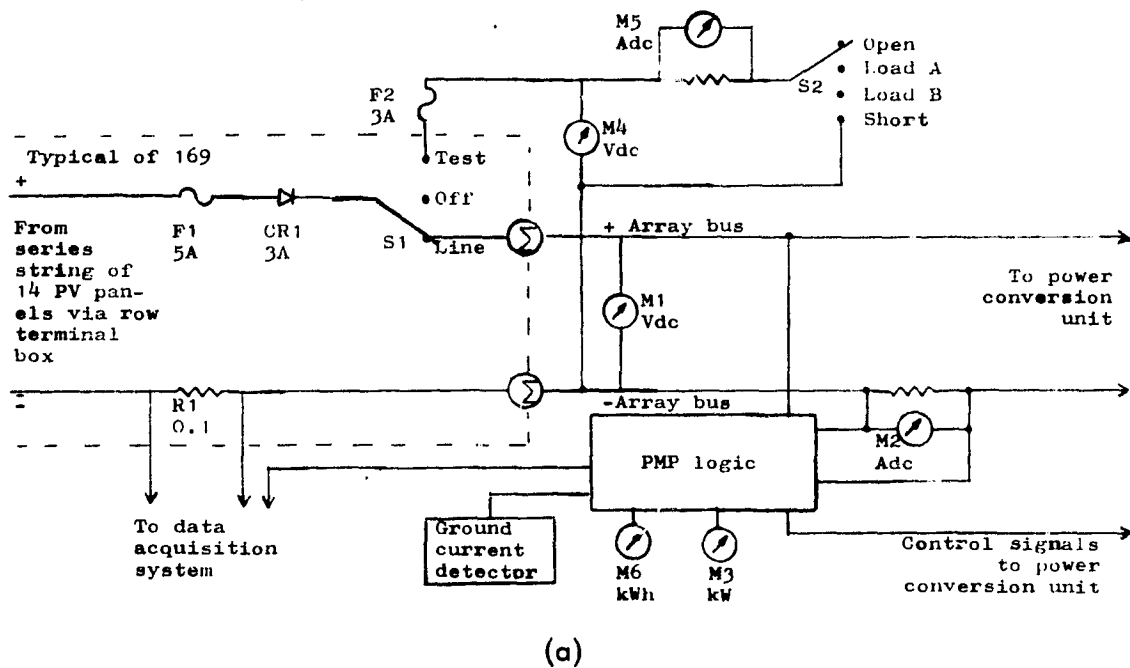
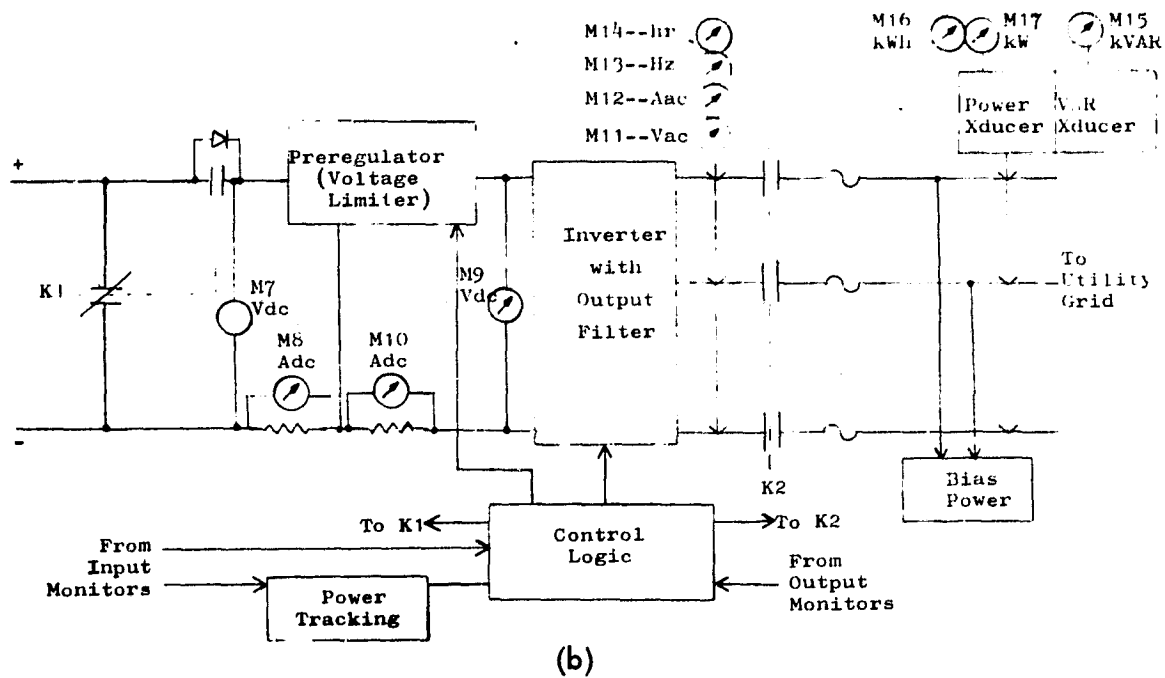


Figure 2-13. PV System: (a) Schematic Diagram of the Paralleling and Monitoring Panel, and (b) Schematic Diagram of the Power Conversion Unit (Courtesy of DECC)

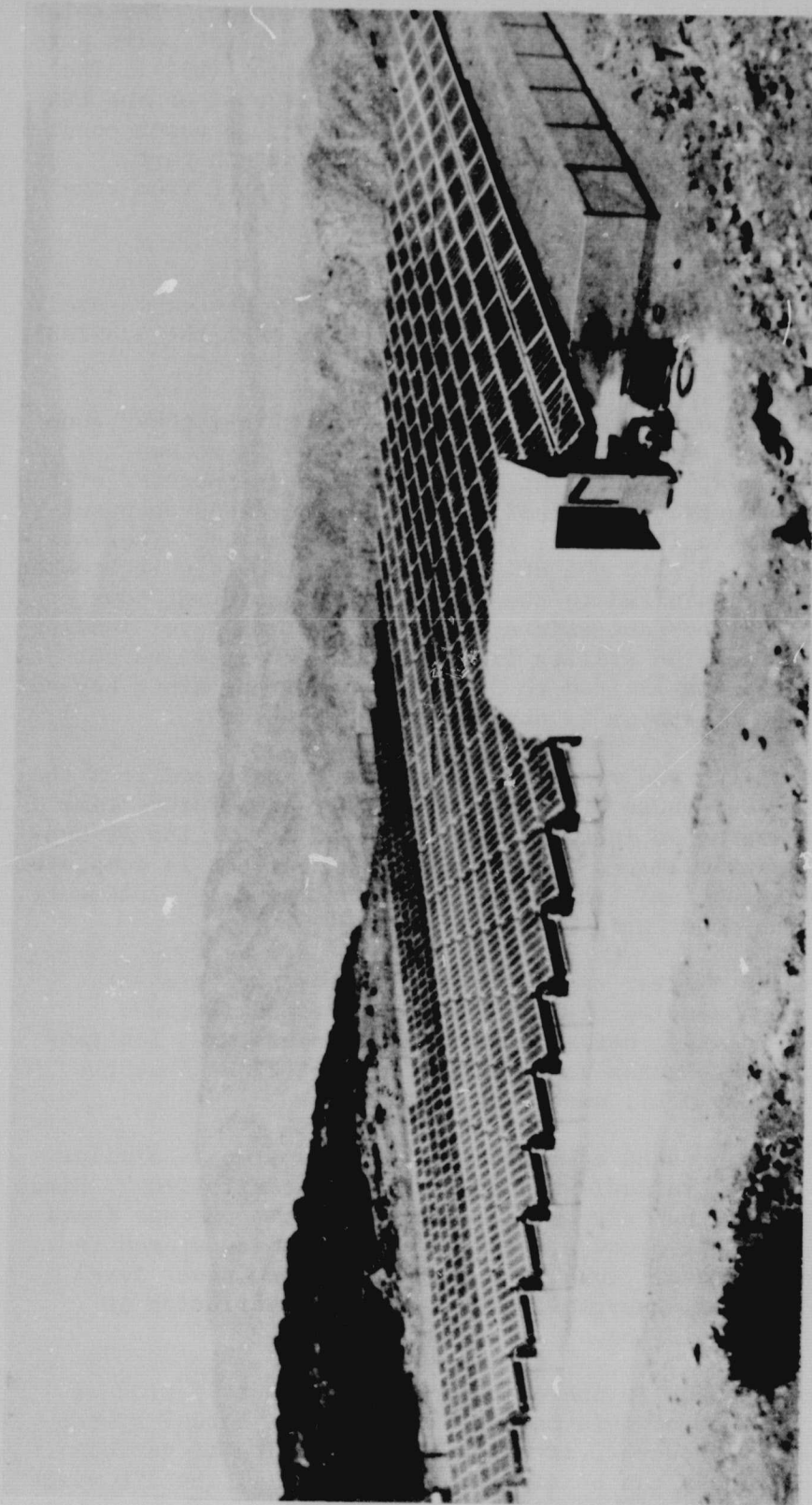


Figure 2-14. Photovoltaics System Site (Courtesy of Mt. Laguna AFB)

The total cost of the project has been reported at 1.3 to 1.6 million dollars; caution must be used in any interpretation. The solar cells cost 1.1 million dollars, however, they were the first units purchased by JPL as part of the Low-Cost Solar Array Project (LSA). The cost contains a large development component. The cost goal of the LSA project is a reduction by a factor of 10. The cost of the power conditioning equipment is reported as \$80K. This is at least in part specially built equipment with some development cost, apart from construction and installation.

e. Operation. The generated power from the PV system is used to provide about 10% of the station's day-time needs. All the available generated power is fed into the power grid.

The operation of the PV system including solar array, power conversion system, start-up, synchronization and shutdown is automatic. Operation on a typical day proceeds as follows. With an increase of the insolation level from darkness the available power increases when sufficient power is available (6 kW) the inverter is activated. The inverter output is synchronized with the utility line and the circuit breaker is closed. Power is transferred to the line. The transfer of power continues until a major decrease exists in the insolation level leading to the flow of power from the utility line into the inverter system. This negative power flow is limited to 2.5 kW and if it persists beyond a few (8) minutes, the PV system is automatically shut down.

Currently, no status and monitoring data are transferred from the PV site to the main power house. It is planned that at a future time a PV system on/off indicator be installed at the plant site. The PV system operates without any commands from the power house. It is completely autonomous with one exception: the power house can manually disconnect the PV system from the power grid.

At the PV site, a digital tape recorder records the value of several parameters on a sampled basis. These parameters include: Array current; array voltage; output power; high temperature; low temperature; the maximum insolation value encountered (1022 W/m^2 at the time of the site visit by JPL); and array power.

The effect of the present operation of the PV system is similar to a negative load (i.e., variable and essentially uncontrolled). Since the load due to radar can be very variable as the radars operate (variation of up to 300 kW), the power system operators are accustomed to large variations in the load. Thus, the 60 kW PV system power level variation is not a problem, especially since any such variation is usually quite slow in developing.

The PV system has been in operation only for a short period of time. Only a small amount of information exists on the actual system operational experience. However, an example of the value of various parameters on a typical day can be cited. At the time of the JPL visit to the site, the real power output was 48 kW, reactive power was 4 kVAR lagging, the DC voltage into the inverter was 220 Vdc, the current input was 240 Adc. The frequency of the power net varied between 59-60 Hz.

This system is expected to have a lifetime of 20 years. Again, since it has only been operative for a short period of time, maintenance requirements are unknown at this time. The first ten years are expected to be maintenance free, and later the possibility exists for purchasing a maintenance contract at a maximum of \$2000 per year.

f. Observation. The Mt. Laguna installation is part of a very large federally sponsored effort in photovoltaics. Part of this effort is concerned with the manufacture of less expensive pure silicon and better, as well as less expensive production of the cells themselves. This federal effort also encompasses full plant demonstrations, such as this project. Reports on progress appear regularly in the press and technical documents; these must be consulted for the up-to-date status.

The array-inverter is completely automatic in operation. A primary objective is to demonstrate unattended, long-term operation. The plant has had no difficulties as far as system operations are concerned. It turns itself on as minimum solar power becomes available in the morning and takes itself off line in the late afternoon. At the present time, there is not even an indication in the diesel plant control area that the solar plant is operating; a simple on-off remote indicator is to be installed. At the present time, the only connection between the plants is a single conduit containing the three-phase power feeders.

A summary of the project design philosophy — as perceived by the authors — concludes this discussion. The total electrical system load at all times exceeds any power level to be available from the solar array; therefore there was never a need for energy storage. The variable output characteristics of the solar cells establish a requirement for a peak power tracking capability which, in effect, determines on a real-time basis the value of voltage and current at the output of the solar cells required for optimum power transfer. This will vary with temperature and insolation. The inverter accepts the direct current and voltage over this range and must perform the DC to AC conversion in an acceptable and efficient manner. With a nominal capability of 60 kW, the Mt. Laguna system was finally constructed with cut-in at a solar array power of 6 kW (1.5 kW output power to the grid) and a shutdown when the available input power was less than 2.5 kW (no output power) for more than 8 minutes. The operating range of the output voltage of the solar cells is 180 to 290 Vdc.

Future plans consist entirely of operation and observation of this demonstration system. No major additions or modifications of the power processing equipment or the interface with the diesel plant are anticipated. Addition of a remote status indicator (planned) or even of remote off-on control is not considered a significant modification. Areas of interest are the long-time operation of the solar cells, their long-time integrity over weather cycles, the expected cleansing action of rain and other such environmental factors.

3. Financial Analysis and Economic Issues

As with the financial analysis of wind systems, the evaluation which follows should not be considered a condemnation of all solar facilities. This PV system was built as an experiment, and to gain operating information. Efforts are underway at a large number of research and manufacturing facilities to improve the viability of solar-powered generating systems.

The photovoltaic system at Mt. Laguna cost \$1.6 million to build and install. Table 2-4 provides an approximate and partial breakdown of these capital costs.

As far as maintenance costs are concerned, the system is expected to be relatively maintenance free for the first ten years, with the possibility of a maintenance contract (of under \$2000/yr) for the final ten years of the system life.

Offsetting these costs will be fuel savings. The Mt. Laguna station expects to save about 35 gallons of diesel fuel per day; since diesel fuel costs about 73¢/gallon, this is an annual savings of \$9,326 on this site. Because it is a government installation, income tax and investment tax credit provisions are assumed not to apply. A brief NPV analysis is shown in Case 1 of Table 2-5; the high capital cost of the PV unit is not justified by the fuel savings.

This information may be used to analyze two utility-connected examples. The Mt. Laguna facility is expected to save 35 gallons of diesel fuel a day because of the PV system; since each gallon of diesel fuel produces 11-12 kWh of energy, this translates into about 403 kWh of electricity per day, or 146,913 kWh annually. If a residential user on the

Table 2-4. Capital Costs for PV System (Approximate)*

Solar Panels	\$1,100,000
Site preparation, foundation, panel frames	140,000
Paralleling and Monitoring	25,000
Power processor	80,000
Non-recurring engineering	220,000
Computer (non-essential) was supplied under separate contract	- -
<hr/>	
TOTAL CAPITAL COSTS	\$1,565,000

* See Appendix B

Table 2-5. NPV Calculations for PV System

		-----Assumptions-----		
NPV Symbol	Variable	Case 1: Remote Site	Case 2: Residential Ownership	Case 3: Utility Ownership
K	Capital Cost, \$1000	1,600.0	1,600.0	1,600.0
C _{O&M}	O&M Cost, \$1000			
	First 10 years	0.0	0.0	0.0
	Second 10 years	2.0	2.0	2.0
R _j , E _f	Value of Electricity Generated/Fuel Saved, \$1000	9.3	3.4	1.9
	Escalation Rates, %			
E _{O&M}	O&M	7.8	7.8	7.8
E _f	Oil	11.3	—	—
E _j	Electricity	—	8.2	8.2
N _s	System Life, years	20	20	20
N _a	Accounting Life, years	10	10	10
r	Discount Rate, %	15	15	15
t _i	Income Tax Rate, %	—	50	50
t _m	Miscellaneous Expense Rate, %	2.5	2.5	2.5
t _c	Investment Tax Credit, %	—	10	10
Formulae for NPV*:		Case 1:	NPV = R _j (14.44097) - C _{O&M} (3.7345372) - K (1.025)	
		Case 2 & 3:	NPV = R _j (11.2095) - C _{O&M} (3.7345372) - K (0.623107)	
Net Present Value, \$1000		-1,513.2	-966.3	-983.1

* * See Appendix A for calculation detail

Southern California Edison System could generate these power levels, the electricity would be worth about \$3,400/yr. This is based on users generating some of their own power needs while connected to the SCE system, paying for electricity under Experimental Rate Schedule D-PG. According to this schedule, users must pay 2.332 cents/kWh for net usage over 300 kWh.

SCE would value this output slightly differently; PV output might allow the utility to conserve on its purchases of power from other utilities. In 1977, purchased power averaged 1.28 cents/kWh.* Thus, the electricity output of the PV system is assumed to be worth about \$1880 (i.e., 1.28 cents/kWh x 146,913 kWh) to SCE.

The last two columns of Table 2-5 show the financial calculations for a residential and utility case. The investment is not profitable in any of the three cases, as shown by the negative NPV; it is somewhat better for the second two cases (even though power savings are lower) because tax provisions are assumed to hold. These capital costs and economic assumptions must be extrapolated to other PV installations with extreme caution. The capital costs are expected to fall rapidly in the next decade. There are also a number of non-recurring costs (for engineering and design) in the calculation which would not be incurred in commercial installations.

One issue SCE has been involved in is setting rate structures and operating guidelines for these dispersed power systems. To permit temporary parallel generation, an agreement between DECC and SCE was submitted to the California Public Utilities Commission in October of 1978. (The safety and metering provisions of this agreement are described below.) The duration of the contract was about 120 days, and during that time SCE bought power back at the same rate it was sold. A service charge of \$40/month was levied against Delta for the duration of the contract: this was the minimum rate for Rate Schedule S (Standby service).

However, this rate agreement is not meant to set a precedent. In a more recent power purchasing agreement (electricity from the Kerr-McGee Chemical Corp. cogeneration plant in the Mojave Desert) SCE agreed to purchase any surplus electricity at a price equal to 85% of its average system cost.** While this is below the marginal cost SCE pays for new energy output, it does reflect the value of the electricity from the new systems to SCE today.

As with the PP&L system, financial analysis shows that the Mt. Laguna photovoltaic project was installed for informational and demonstration reasons, rather than profit motives.

*Source: Annual Report of SCE to the Federal Energy Regulatory Commission, December 31, 1977.

**Source: "From the Mojave," The Energy Daily, Tuesday, August 7, 1979, p. 4.

4. Institutional and Environmental Issues

a. Capacity Problems. Although the PV system was not designed for permanent installation on the SCE system, let us examine the situation from that point of view. When compared with the other two cases studied, SCE has less immediate capacity problems: its planned reserve margin at peak is about 23.1%.* However, a large portion of SCE's planned capacity additions in the next decade are nuclear generators (such as San Onofre 2-3, Palo Verde 1-3). A number of California nuclear laws, passed in 1976, may act to constrain development of nuclear power plants in the State because of issues surrounding the long-term storage of nuclear waste and reprocessing of nuclear fuels. SCE has challenged the constitutionality of these laws,* but it continues to face public and regulatory problems in development of its nuclear capacity.

Another issue which will influence SCE capacity is the number of air quality standards currently under consideration. The California Air Resources Board has adopted a rule which requires a 50% reduction in NO_x emissions by 1982, with a further reduction to 10% of presently permitted values by 1990 for electric utilities in the South Coast Air Basin. In addition, the South Coast Air Quality Management District has proposed a rule requiring SCE to reduce the sulfur content of its fuel oil from 0.25% to 0.1%, or install sulfur oxide removal equipment on its plants to achieve a similar emissions level by January 1, 1983. Both of these regulations have induced SCE to seek out alternative forms of generation.

b. Safety Issues. When SCE agreed to allow parallel generation of power by Delta Electronics, a number of safety and metering conditions were written into the contract: these conditions may have been peculiar to the DECC contract, because the temporary nature of the project (originally 60 days) did not warrant installation of special metering to measure backfeed into the utility.

- (1) Output of the PV system was not to exceed 30 kW.
- (2) Protective devices for preventing damage to the PV system were the responsibility of Delta. Controls on the PV system were to be designed to prevent backfeeding of energy into a dead line.
- (3) DECC could not permit the solar output to exceed the connected load of its facilities; this made additional metering unnecessary, and protected SCE from later inquiries about payment for excess energy during the ostensibly temporary test period.

*Source: SCE 1978 Annual Report.

- (4) When it became necessary for SCE to work on the distribution line serving Delta, either Delta-owned or SCE-owned switches would be utilized to disconnect DECC from the system. (The switches were already installed; no new installation was required.) If requested by SCE, DECC was to open its disconnect switches for verification of position.
- (5) Delta released and discharged SCE from all claims against SCE arising from parallel generation of the PV unit. Delta was to indemnify and hold harmless SCE from all liability, damages, costs, losses, etc., resulting from parallel generation.

After the PV system was moved to Mt. Laguna, a chain link fence enclosed the system.

c. Licensing Procedures. Many of the problems associated with operating or installing a PV system were not encountered in this case study. The initial system testing was done on Delta Electronics property, and later operation has been carried out on government land at Mt. Laguna. The main interaction with regulatory agencies occurred when Delta and SCE entered into a parallel generation agreement; the contract was not effective until the California Public Utility Commission Approval was received.

d. Resource Availability. Mt. Laguna was chosen as the photovoltaic test site because of the high insolation levels it receives. In addition to having a large number of clear days, it receives about 1100 W/m² of sunlight during most of the day; this is higher than most regions.

C. COGENERATION

1. Introduction

San Diego Gas and Electric Company (SDG&E) is the smallest of the three utilities examined in this study. Like SCE, it has a higher summer peak demand and uses large quantities of oil and gas for electricity generation.

In 1968, SDG&E established Applied Energy, Inc. (AEI), a wholly owned subsidiary, to handle all of its industrial cogeneration activities. AEI is involved only in the manufacture of steam and its sale. The four steam-producing facilities owned by AEI and employing cogeneration technology are not operated by AEI. Exhaust heat from SDG&E turbines is purchased by AEI and used to manufacture steam. This steam is used by AEI customers which includes Rohr and the U.S. Naval Public Works at three sites in San Diego for industrial processing, space heating and shipboard uses.

AEI was established to streamline legal involvements and to keep all contractual and administrative problems in a separate profit center. It cannot purchase industrially generated power nor can AEI generate electricity due to Security Exchange Commission regulations. Arrangements for industrial cogeneration must be coordinated in SDG&E power contracts if an industrial firm wishes to own and operate the generating equipment.

In January 1977 Mr. Archie Kelly of ERDA suggested a small cogeneration project with Rohr Industries at their Chula Vista plant (see Figure 2-15); SDG&E and Applied Energy were ready to participate, and an agreement satisfactory to all parties was reached. The three-way contracts were signed in September 1977: steam delivery between Rohr and Applied Energy; waste heat delivery between Applied Energy and SDG&E; and site lease and emergency electrical power between SDG&E and Rohr.

The installation is relatively small compared with other SDG&E steam contracts and with other identified potential cogeneration tasks in California (Ref. 23).

The contract specifies a 10-year period with a renewal for a second 10 years; continued stable operation of the commercial venture is one of the major ingredients of a cogeneration operation. An additional circumstance in this case is the use of the locally generated power as emergency back-up power for the Rohr computer complex; this certainly was a positive factor in the decision to carry out the project.

2. System Information

a. System Description. The Saturn gas turbine manufactured by Solar Division of International Harvester of San Diego is rated at 800 kW. It is an industrial-type turbine suitable for continuous extended operation. SDG&E previously had several of these relatively small units operating on natural gas. The Rohr unit presently uses Diesel No. 2 fuel. The several Rohr standby and peaking steam boilers will use the same full supply when it is required to operate them and the natural gas supply is curtailed.

Steam is produced in a Deltak heat-recovery (from turbine exhaust) boiler capable of 7000 lb of steam per hour at 13 psig. Because of the low steam pressure, unattended operation is permitted.

The plant is controlled from SDG&E's Station B located about 10 miles away in downtown San Diego. The original control and monitoring equipment operates satisfactorily, however, major control rework will be done. A main reason is to provide more precise gas turbine load control.

b. Load and Local Utility Connection Characteristics. In addition to the electrical aspects, those related to the steam generation will be discussed here.

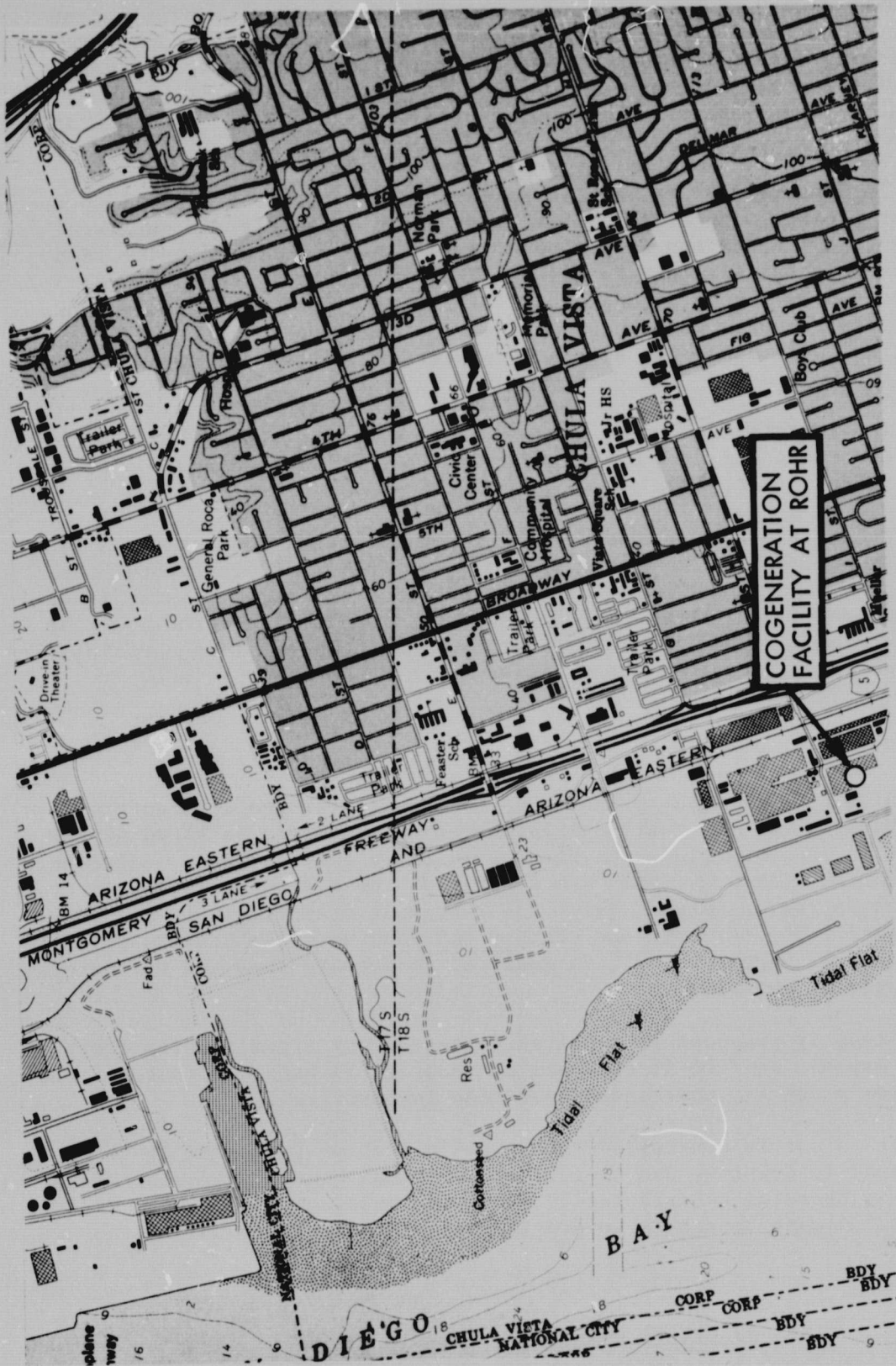


Figure 2-15. Geographical Location of Cogeneration Facility at Rohr
(SDG&E Service Territory)

In the Chula Vista complex the Rohr plant load is about 6 MW. Rohr is a large customer for SDG&E. Rohr is a "clean" customer with well managed changes in electrical load and a minimum of plant/utility interface problems. Tie-in is to a 12 kV distribution feeder. Figure 2-16 shows the single-line diagram of the system connection. The 800 kW locally generated power is delivered into this same feeder and reduces the power delivered from the utility substation by about 13% under normal power flow conditions.

Operation under emergency conditions is one of the most interesting, if not one of the most important aspects of this installation. When planned or unplanned outages of the 12 kV utility line occur, the local 800 kW source is isolated from the inoperative line and supplies about 650 kW to the Rohr plant's computer complex. The negotiated agreement includes utility supplied switchgear, additional metering, and standby charges to Rohr. The significant point is that this installation provided the opportunity, identified and suggested first by Rohr, for SDG&E to provide a total electrical requirements package to Rohr without Rohr's operational involvement.

Steam is used in a metal plating operation both in a return condensate process and an open vented mode for plant cleaning. Make-up water is about 15%. During the normal work week the steam load is continuous, 24 hours per day. The small dips at lunch breaks and shift changes are absorbed in the reservoir capacity of the steam system; it is not necessary to change the operation of the gas turbine. A reduced quantity of steam is needed over the weekend when, particularly on Sundays and holidays, this plant equipment is kept hot but is not in production. Rohr's energy conservation program has minimized weekend losses. There is provision for exhausting unneeded gas turbine exhaust if it is desirable to operate the gas turbine-alternator at higher electrical capacity than the steam delivery requirement.

Thus, from the point of view of the utility, the electrical capacity of the unit can be considered firm; and, in fact, it can be available at all times except during occasional maintenance periods. Rohr does maintain standby boilers for these occasions as well as the peak steam demands in winter which exceed the 7000 lb/h cogeneration plant capability.

c. Site. The gas turbine unit is located on Rohr property at their plant in Chula Vista, California on the east side of San Diego Bay. No particularly special site preparation was necessary. Three 12,000 gallon underground tanks for storage of the Diesel No. 2 fuel were installed; the Rohr boilers had been using propane as their standby fuel but were modified to burn oil to be taken from the turbine storage tanks during natural gas curtailments.

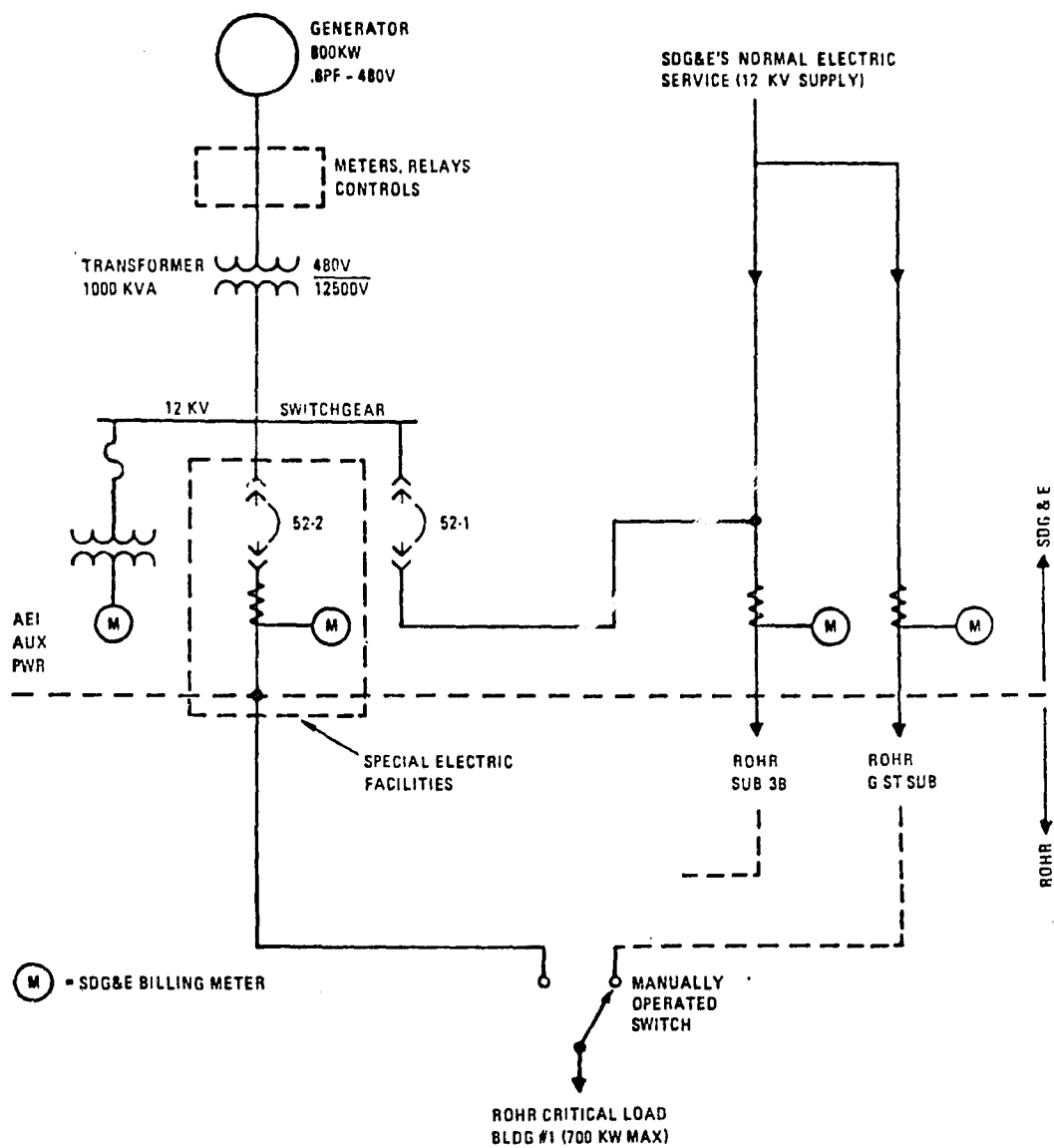


Figure 2-16. Single-Line Diagram Showing the Cogeneration System Connection (Courtesy AEI)

d. Construction. With the contracts in force in September 1977 on-site construction started in February 1978. The turbine and major equipment were installed by mid-April. The last of the electrical equipment did not arrive until October. The plant was in operation starting the fifth of February 1979. Approximate total cost was \$850,000.

e. Operations. After a straightforward start-up period, the plant has been operated without difficulty. The capability of the remote control system is being increased to provide remote startup and shutdown from the SDG&E Load Control Center.

Typical operation level has been 700 kW gross with about 660 kW net. Steam rate has varied between 6500 and 4000 lb/hr. SDG&E considers the electrical source to be firm and can choose to operate it at all times by bypassing the unneeded gas turbine exhaust. It is important to note that SDG&E has ultimate control of the electricity at all the AEI plants; SDG&E can generate electrical power independent of the steam load at all sites at any time.

f. Observation. The technologies and techniques are quite standard; the basic gas turbine-generator plant, the generation of steam with the heat exchanger, the primary connection to the power grid and the remote control of the unit.

Some of the unique features are the three-way contractual structure, the economic facets, and the emergency power connection to the computer complex.

Future plans for this project consist essentially of continued commercial operation. Apart from the control system update nothing additional is planned.

3. Financial Analysis and Economic Issues

The San Diego cogeneration facility was the only case study in which an agreement was made between two private corporations (SDG&E, along with its subsidiary, AEI, and Rohr Industries) without government participation in the project. The arrangement was beneficial to all parties involved. However, exact financial information on the arrangement is not available, since some of the information is proprietary. Further, Rohr's bill for steam usage is based on the value of exhaust steam, which includes the current prices of fuels used to operate the turbine, less a credit (the \$/kWh value was not available to the authors) for electricity produced by the system.* Because the information is not completely accessible, the financial analysis which follows is based on some general assumptions which may not reflect the actual AEI-Rohr-SDG&E operating situation, and should not be construed as doing so.

*A more complete discussion of these arrangements is contained in Appendix D of H. Davis et.al. Potential for Cogeneration of Heat and Electricity in California Industry - Phase I, and II. JPL Publication, 78-42, and 78-109, May 1, 1978, and January 1, 1979 respectively.

Table 2-6 lists the capital and operating assumptions made in the cogeneration case. It is assumed that net electricity output averages 660 kW continuously, and this electricity output is valued at 2.332 cents/kWh (other rate schedules can be assumed). About 12.5×10^6 Btu/hr of fuel is needed to run the turbine; this can currently be obtained at about \$3.6 per million Btu by utilities in the Pacific region.* Finally the average steam rate was assumed to be 5750 lb/hr, since the short-term rate varied between 4000 and 6500 lb/hr.

Given the costs and operating assumptions of Table 2-6, a utility or industry might be interested in calculating the price for which it must sell steam in order to recoup its initial investment. This calculation is done in Table 2-7: selling steam at \$8.05/1000 lb would allow the cogenerator to breakeven on the system. Since most cogeneration facilities currently quote a price of \$4/1000 lb for steam, this price is relatively high.

Many factors can change the profitability of such a cogeneration system. If the prices at which electricity or steam may be sold increase, the investment is more profitable. If the cogenerator must buy fuel on the open market (where prices are currently about \$6 per million Btu) the investment is less attractive. Many utilities have had long-term fuel contracts, reflecting earlier, lower prices. Thus, if utilities are able to obtain fuel at prices below those of the current market while non-utility cogenerators could not, an arrangement under which utilities produced the steam and sold it to industry (at less than industry could produce the steam for) would be beneficial to both parties.

Table 2-6. Cost and Operating Assumptions - Cogeneration

Initial Capital Cost (includes gas turbine generator, boiler, underground fuel oil storage, controls, piping)	\$850,000
Operating Expenses	10,000/yr
Maintenance Expenses	25,000/yr
Fuel Costs (\$3.6 per million Btu x 12.5×10^6 Btu/hr)	394,200/yr
Electricity Output (660 kW net x 8760 h)	5,781,600 kWh
Steam Output (5750 lb/h x 8760 h)	43,800,000 lb/yr

*Source: DRI Energy Review.

Table 2-7. Breakeven Calculations for Cogeneration Facility

<u>NPV Symbol</u> (See App. 2)	<u>Variable</u>	
K	Capital Cost, \$1000	850.0
C _{O&M}	O&M Cost, \$1000	35.0
C _f	Cost of Fuel, \$1000	394.2
R _j	Value of Electricity generated/saved, \$1000	134.7
R _j	Value of Steam generated/saved, \$1000	- Variable -
	Escalation Rates, %	
E _{O&M}	O&M	7.8
E _f , E _j	Fuel/Steam	11.3
E _j	Electricity	8.2
N _s	System Life, yrs	20
N _a	Accounting Life, yrs	10
r	Discount Rate, %	15
t _i	Income Tax Rate, %	50
t _m	Misc. Expense Rate, %	2.5
t _c	Investment Tax Credit, %	10

Calculating Steam Price: $P = [K(.623107) + C_{O\&M}(10.8635) + C_f(14.44097) - R_j(11.2095)] / (14.44097)$
(43.800)

Breakeven Sales Price for Steam: \$8.05/1000 lb

The analysis contained in Table 2-7 explores a scenario under which the cogenerator owned all the equipment, purchased fuels, and sold by-product steam and electricity. In this case study, those functions were divided among the three parties involved. SDG&E owned the turbine equipment and "purchased" the electricity from the generation process by giving AEI a credit for the Btu equivalent of the output. AEI acted as a steam contractor: it operated the turbines and sold the steam output to Rohr.

The benefits of this arrangement to Rohr Industries were not limited to steam agreements; Mr. Bob Miller of Rohr commented that Rohr was not saving any money by purchasing the steam. The main benefits to Rohr came from a pair of contractual options which made the company's electric and fuel supplies more secure. The first option allows Rohr to use the 800 kW generating capacity for its computer operations in the event of a power failure. Secondly, Rohr is on interruptible gas service; if its gas service were cut off, Rohr could continue its operations by using fuel stored for use by the cogeneration turbines. If these options had not been available, Rohr would have had to build a computer back-up system and an oil back-up facility; these would have cost about \$250,000 and \$100,000, respectively.

This case was the one in which the primary motivations were economic — to increase the useful output from expensive fossil fuels, to limit the costs of an electricity failure or natural gas cutoff, and to augment electricity capacity. The form of the cogeneration arrangement was motivated by institutional and environmental problems facing SDG&E, as discussed in the next subsection.

4. Institutional and Environmental Issues

a. Capacity Problems. Of the three utilities studied, SDG&E is faced with the greatest capacity problems. The inexpensive hydropower it has been receiving from the Northwest cannot be counted on as being available after the mid-1980s, as the contracts expire.* In May, 1978, the company halted work on the proposed Sundesert nuclear project, after the Public Utilities Commission issued an order that effectively denied SDG&E authorization to continue investing funds in the project. Sundesert would have added significant capacity to the system. Plans to repower an oil-fired unit at Silver Gate Power Plant were cancelled in December 1978 because of emerging federal policies against new oil-fired generation.** These losses in generating capacity may be replaced by increased purchases of power from other utilities, including Arizona Public Service, Tucson Gas & Electric Company, and the Mexican utility, Comision Federal de Electricidad. Thus, SDG&E is trying to pursue a variety of new generation options.

b. Safety Issues. The safety situation at the AEI facility is similar to most small turbine installations. However, since the AEI facility is on Rohr property, a problem of liability and access arises, which so far has been resolved by having AEI personnel check the facility each day, rather than leaving check-up to Rohr personnel.

*Source: R. Gurfield and C. Davis, Electric Energy Costs of Southwestern U.S. Utilities to the Year 2000. JPL Document 5103-62, April 15, 1979.

**Source: SDG&E Annual Report 1978.

c. Licensing Procedures. The main problems and delays in setting up the Rohr facility came from environmental regulations. Three programs currently administered by the U.S. Environmental Protection Agency (EPA) which affect cogeneration are the New Source Performance Standards (NSPS), Prevention of Significant Deterioration (PSD) and New Source Review (NSR) regulations. The standards of performance for new stationary sources are enforced by the local Air Pollution Control Districts (APCDs) according to guidelines set by the EPA; California versions of the second two regulations are under development by the state Air Resources Board (ARB).*

The NSPS rules specify pollution levels for new or modified stationary sources, including fossil-fuel-fired steam generators. The standards apply to fossil-fuel-fired boilers of more than 250 million Btu per hour of heat input. The Rohr facility is the largest generator which can meet the APCD rules for the levels of contaminant in the air without the use of scrubbers. Although it took a long time to get the APCD permit, the AEI facility does not need scrubbers.

The other major regulation affecting cogeneration concerns plant siting. Utility-owned plants in California are subject to the complete Notice of Intent/Application for Construction permit procedure administered by the California Energy Resources Conservation and Development Commission (CERCDC). The legal procedure is expected to take up to 36 months, but in practice usually takes much longer. Plants between 50 and 100 MW can expedite the procedure under the Same Power Plant Exemption; power plants under 50 MW are not in the jurisdiction of the CERCDC.

d. Resource Availability. The Rohr facility represents a unique opportunity for cogeneration because it requires large amounts of steam continuously. From the utility side, SDG&E has had considerable experience in the operating of small dispersed units of oil and gas-fired turbines. This combination of operating characteristics and operating experience made the Rohr-AEI cogeneration arrangement a mutually beneficial one.

*A more detailed description of these regulations may be found in Appendix H of the H. Davis report on cogeneration (Ref. 23).

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SECTION III

ANALYSIS AND CONCLUSIONS

This portion of the report summarizes the current and future implications of DSG. Subsection A presents a check list and description of the technical, economic, institutional and environmental issues which will face future dispersed generation and storage systems. Not all of the issues listed were faced by the three cases described in this report. Subsection A divides these issues into those that were addressed by these case studies, and the issues which have not yet been addressed.

As far as possible, the three DSG examples studied in Part II of this report have been used to indicate future issues and trends. The first part of subsection B extends consideration of each individual case to similar technologies in other locations. For example, information obtained from PP&L's wind generation system is used to suggest how wind generation might be applied in other sections of the country. In the second part of subsection B more general conclusions are drawn; the problems and issues faced by these three case studies are extrapolated to other DSG systems. A final subsection contains conclusions and recommendations for future research.

A. INTEGRATION AND ANALYSIS OF CASE STUDIES

This subsection summarizes the issues and problems discussed in Section II using four tables. To be included in the tables, a topic had to meet one of two criteria. Either an item had to be unique to at least one of the DSG cases studied, or it would have to be a possible consideration in a future installation. For example, the stability of the AC system is an issue for this particular photovoltaics system in its ultimate application: however, the design of cabling and duct work is not an area peculiar to DSG, nor is it necessary to consider this question in particular depth in any of the DSG installations. Consequently, the stability of the AC system is included in the technical part of the table, whereas the design of cabling and duct work is not included.

1. Technical Issues

The technical issues have been divided into four main categories: Design Considerations, Operation, Maintenance, and Protection. These issues, which are tabulated in Table 3-1 are discussed next.

Design Considerations

There are relatively few design considerations peculiar to DSG. In fact, for the cogeneration case considered here none could be identified. However, both the wind turbine generation and the PV systems made use of a dc to ac inverter; the type of inverter used and the manner in

Table 3-1. Technical Issues

	WTG	PV	COGEN
<u>Design Considerations</u>			
Inverter type	X	X	
Security-fencing, spacing	X	X	
Grounding		X	
Auxiliary equipment uniqueness			
<u>Operation</u>			
Availability of resource	X	X	X
Loading-base/intermediate/peak	X	X	X
Storage	X		
Power infeed not permitted		(X)	
Stability of utility system		X	
Manned/unmanned			
Real-time monitoring	X	X	
Recording			
Abnormal conditions	X		
Harmonics			
Short-term stability resource	X		
<u>Maintenance</u>			
Icing of blades	X		
Frequency			
Complexity			
Responsibility			X
Replacement parts/hardware			
<u>Protection</u>			
Utility system	X	(X)	X
DSG system	X	X	X
Legend: X = Explicitly identified by organizations considered. (X) = True at DECC and not at Mt. Laguna AFS.			

which it is controlled are clearly considerations of the designer. In both cases, it is expected that the DSG would be operated for maximum power. In view of the remoteness of the location and the probability that it would be unmanned, security fencing was needed at the wind turbine generator site and the photovoltaic site. The spacing of the photovoltaics arrays is a design question; in addition to consideration of shadows, sufficient space must be left for proper access to the solar panels.*

It is conceivable that equipment unique to a DSG installation would be developed: examples of such equipment include means of controlling turbine blade angles, sun tracking solar arrays, and so on. In the cases studied this equipment was not used: however, this item is included in Table 3-1 because of its potential occurrence in the future.

Operation

Several issues regarding the operation of the system were raised in the cases studied here. For example, the availability of the energy resource was considered to be of interest in all three cases, although for different reasons. In the case of the wind generation and the photovoltaics systems, the resource is intermittent and essentially uncontrollable, whereas for cogeneration the resource is oil which is a scarce fuel.

A similar issue is the loading of the unit (whether it should be considered and operated as base load, intermediate, or peaking capacity). This is a question of interest to the system operators. For the wind turbine and the photovoltaics systems, of course, the desire would be to run the units at maximum power at all times. And, in the case of the cogeneration, the electrical power available is essentially a function of the industrial plant which is the primary user of the heat energy. However, by means of the appropriate contractual agreements, the cogenerated power can be firm.

Only in the case of the wind generation system was dedicated storage considered.

In the case of the wind generation system and the cogeneration facility, it was planned that there could be a net flow of energy into the utility distribution system. For photovoltaics system, however, this was specifically forbidden in the test installation. At the Mt. Laguna location, the photovoltaics system's output is routinely inserted into the power distribution network.

*Since the interviews reported here, it has been learned that difficulties have been experienced with the solar cells at Mt. Laguna. It is thought that these problems are cell design or fabrication problems, and are manufacturer rather than system problems.

At Mt. Laguna the photovoltaics system was installed on a relatively small isolated power system, where the percentage infeed from the solar arrays formed a significant proportion of the total system capacity. Because of this and the fact that the input power varies in an uncontrolled fashion, the question of stability of the power system was examined, although no problems were encountered. Any unique impacts on system stability due to DSG were not considered to be a problem with the wind generation system because of its very small size, and, in the case of the cogeneration, because of the similarity in conventional generation, i.e., controllability of generation.

The question of whether the generation station should be manned or unmanned was not an issue in the cases studied here. It could conceivably be a question of interest, however, in future installations.

The photovoltaics installation and the wind generation system were both installed largely to gain information about the operation of such systems. As a consequence, a real-time monitoring system was installed for these systems which might otherwise have not been needed. The cogeneration installation was relatively standard, and no real-time monitoring was incorporated.

Recording equipment (such as strip chart recorders) which might normally find use in the generating station was not installed for any of these installations for normal operation.

Abnormal conditions can occur with the wind generation system. For example, a wind considerably in excess of the design wind speed for the turbine blades could cause operating problems, and, therefore, the system had to be able to operate safely through such a situation. This type of contingency does not apply to the photovoltaics system or the cogeneration facility.

The question of harmonics arises in the case of some inverter types that may be used with a dc system. For example, if a six pulse inverter is used and the ratio of inverter power to total system power is fairly large, harmonic filtering on the ac side must be sufficient to insure proper operation of the inverter. In no case was this a problem with any of the installations considered here.

The short term stability of the resource is a question of relevance to the wind generation system. Here gusting can cause changes in the power available in a matter of seconds. In general, this does not occur with cogeneration or photovoltaics.

Maintenance

Maintenance of the equipment was not considered to be an issue with any of the cases studied here, with the exception of the cogeneration facility where the division of responsibility for maintenance was delineated in the operating agreement between parties involved.

Protection

The issue of protection, both of the utility system and of the DSG is worthy of special consideration. Certainly the existence of a generation source on the distribution system is a feature that most existing protection schemes are not designed to cover. Broadly speaking, the operation and maintenance practices of the utility companies do not recognize the possibility of there being a source of generation out on the distribution, or at substation locations on the low voltage side. Consequently, all of these DSGs raised significant issues concerning the protection and operation of the utility system to which they were connected.

Similarly, protection of the DSG from problems which may occur on the power system were also considered in each of these installations. These technical problems are not difficult to solve. For example, an inverter may be controlled so as to prevent reverse power flow when desired. Steps may be taken to assure that the electric power system does not drive a synchronous generator as a motor. While no unusual problems were identified, all the cases studied here required special consideration as far as protection is concerned. This introduces additional complexity in the coordination of the protection of the DSG and of the utility.

In the case of the PV system, the question of safety necessitates an adequate grounding system over a large area. Thus, the grounding of the system becomes an issue for the photovoltaics installation.

2. Cost Components

Table 3-2 lists all items of expenditure which affect the cost of an installation. These costs are broken down into three categories: expenditures which will have to be made throughout the lifetime of the system (recurrent costs), one-time costs necessary to purchase and install the system, and any special equipment used to provide information and make tests.

Recurrent costs include expenditures made throughout the system lifetime; the category also includes anticipated increases in these costs over time. Thus, expected increases in the price of fuel and electricity were important considerations in the cogeneration case; operating and maintenance arrangements were also taken into account. However, since the wind generation and photovoltaics systems were primarily test sites, these recurrent costs were not well known, and were not primary considerations when installing the systems.

Non-recurrent costs include all expenditures necessary to make the DSG system operable. While the main costs are usually basic equipment costs, there are also expenditures associated with obtaining zoning and environmental permits, site and foundation preparation, and safety and back-up equipment. For example, the arrangements made in the cogeneration facility case made it unnecessary for Rohr Industries

Table 3-2. Cost Components

	WTG	PV	COGEN
<u>System Costs</u>			
Recurrent Costs			
Operation			X
Maintenance			X
Fuel Input			X
Electricity			X
Nonrecurrent Costs			
Initial Investment			X
Safety Equipment			X
Environmental Additions			
Installation/Site Preparation	X		X
Permit Process			X
Back-up Equipment			X
Special Equipment Costs (Costs of equipment used for testing and information gathering which is not essential for operation)			
Data Acquisition Equipment	X	X	
Control or Protection System			
Changes to Facilities Tests	X	X	
Legend: X = Explicitly identified by organizations concerned.			

to acquire back-up equipment. Although the cogeneration facility had to file an environmental impact statement (included under the permit process category), no additional environmental equipment was necessary. However, all other nonrecurrent costs were important in the installation of the cogeneration facility. Many of these cost considerations were not important for the other two case studies; since these were prototype systems, basic equipment costs and permit procedures were not yet standardized. While these costs will be important to future wind and photovoltaic systems, they were not central considerations here.

The final cost category includes special equipment which is not essential for the operation of a DSG system. This includes any equipment used for data acquisition and processing, and any equipment additions used to protect the system while tests are underway. Special equipment was an important part of the system cost for the wind turbine and photovoltaic facilities.

3. Environmental Issues

The environmental issues are summarized in Table 3-3. The various forms of pollution are a major part of this category. The cogeneration facility had to conform to California's air quality standards; audible noise was also a consideration at the Rohr facility. In contrast, pollution problems for the wind turbine focused on audible noise, radio and TV interference, and the visual aspects of the turbine design.

Three other categories of environmental issues exist. The first is waste disposal. This issue was not considered by any of the three case studies. However, this may be important for such dispersed storage systems as batteries and fuel cells, where the chemicals contained in the system at the end of its lifetime must be disposed of.

The second issue is land use. If DSG systems become a significant source of electricity, the quantities of land they use will become an important issue. If these facilities are dispersed among residential and industrial users, they may displace housing and recreational uses.

The final consideration is a more general one. An attempt is made to consider the effect of a new DSG system on the surrounding animal and plant life. In these three case studies, the only effect mentioned was that of bird migration upon the wind turbine generation system. However, it is also possible that at some future time large quantities of land area covered by wind turbines and photovoltaic systems might disrupt the local biosystem.

4. Economic/Institutional Issues

The first issue in this category, which is tabulated in Table 3-4, is safety. Protection of the utility and DSG system were discussed under technical issues, and they are not considered here. This category focuses upon the liability problems which must be resolved when a small

Table 3-3. Environmental Issues

	WTG	PV	COGEN
<u>Pollution</u>			
Air			X
Water			
Audible Noise	X		X
Radio/TV Interference	X		
Visual	X		
Low Frequency Electric Field			
<u>Waste Disposal</u>			
<u>Land Use</u>			
<u>Ecology - Biosystems</u>			
Flora			
Fauna	X (birds)		

Table 3-4. Economic/Institutional Issues

	WTG	PV	COGEN
<u>Safety/Liability</u>	X	X	X
<u>Regulations</u>			
Zoning Laws	X	X	X
EIS			X
Rate Structure/Review			X
Tax Arrangements			X
Fuel Use Laws			X
<u>Public Acceptance</u>			
<u>Infrastructure</u> (Utility organization, personnel assignments)			

Legend: X = Explicitly identified by organizations considered.

power producer is connected to the local utility. For all three facilities, this was an important consideration. The cogeneration facility had to face the issue of having Rohr Industries personnel maintain the equipment which connected them to the utility. All three facilities had to consider safety hazards to the surrounding community.

The second category includes the wide variety of regulations under which each system must operate. All three facilities had to consider local zoning ordinances when locating the facility. While only the cogeneration facility had to file an environmental impact statement (EIS), this will be an important report for future DSG systems. Another significant regulation, which is currently undergoing a large amount of change, governs the rate structures which apply to small power producers. Currently, Section 210 of the Public Utility Regulatory Policies Act (PURPA) suggests guidelines for agreements to sell and purchase electricity between small power producers and the local electric utility. If these rate structures become standardized, it will be much easier for small generation facilities to connect to local utilities. Another issue which small power producers will face is the tax arrangements under which they operate. If tax credits or subsidies are given to solar and other small power producing facilities, these tax incentives will encourage the adoption of DSG systems. For the Rohr case study, the possible cutoff of natural gas was an important consideration in building the cogeneration facility.

Another institutional consideration is public acceptance. Favorable perceptions of solar energy and cogeneration have supported the development of these DSG technologies. However, if some technologies are perceived to require large amounts of desirable land, or have safety hazards associated with them, public acceptance may decline.

Another issue will be that of infrastructure. These case studies represent very small quantities of generation. Thus, they have equally small impacts on the utility. However, if future DSG systems represent a significant portion of electricity generation, utilities may have to focus more on distribution and reorganize their capital mix and personnel resources accordingly. Furthermore, DSG systems will require maintenance and meter reading services; it is not clear at this time whether utility personnel, or new independent businesses, will handle these services.

B. GENERIC ANALYSIS

The preceding sections of this report have focused upon information synthesized from the three DSG cases. This portion of the report extends the scope of analysis in two distinct ways. First, the information from each specific case which may be useful when installing similar technologies in other locations or uses is extracted. Thus, the lessons learned from PP&L's wind turbine generator, the Mt. Laguna PV system and the AEI cogeneration system, are applied to wind generation, PV and cogeneration systems in other sites, respectively. Second, this analysis is taken one step further, and the issues raised in these three cases are generalized to other DSG technologies. The basic issues affecting the viability of dispersed systems are surveyed.

1. Application to Other Sites

a. Wind Generation Systems. Seven major issues were identified to be pertinent to other wind systems. These were: resource availability, site selection, power processing, environmental effects, impact on bird migration, capital costs, and public acceptance. Each of these issues is discussed below.

Availability of wind is a primary factor in the selection of a WTG. The site chosen for the wind system must receive adequate amounts of wind, and these wind levels should not be subject to wide fluctuations. The power output of a WTG system is very highly dependent upon wind velocity. For example, the PP&L system had a rated output of 45 kilowatts; this can be achieved at wind speed of 27 mph. However, at a wind speed of 12 mph, only 6 kW is generated. Since the profitability of a WTG system depends on the amount of electrical energy generated, and the electricity generated so greatly depends upon the amount of wind available at the site, wind speed and the fluctuations in that speed will be important factors in the choice of wind generation system. Prior to site selection, it may be necessary to conduct a detailed survey of how much wind and of what intensity, speed and continuity a given potential site receives over an extended time. These data can be used to establish the suitability of the site or, if a site is selected, wind data can be used to establish the rating of the WTG system to be installed.

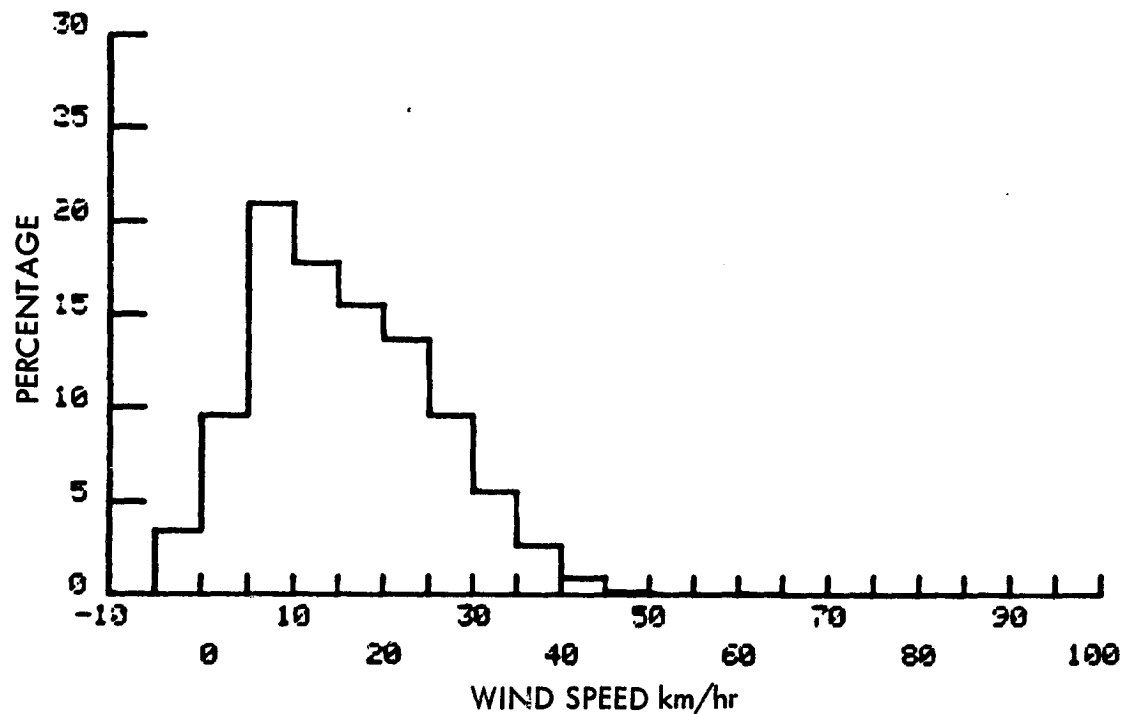
As an example of the type of data which could be used to establish WTG potential, data are presented in Figures 3-1 to 3-4. Histogram and cumulative frequency information is shown for the distribution of wind velocity data over a period of one year. The data were furnished by the American Electric Power Service Corporation, from measurements made at the AEP-ASEA Ultra High Voltage station in North Liberty, Indiana.

The results are presented in four periods, each corresponding to a quarter of the year (1979). Median wind velocities were:

Jan - March	14.5 km/hr
April - June	11.3 km/hr
July - Sept	6.5 km/hr
Oct - Dec	15.6 km/hr

It is evident from the indicated population size that data were not collected for the entire period; nevertheless, the number of readings obtained (> 33000) at regular 10 minute intervals is statistically large, and can be taken as representative. The annual median wind velocity is approximately 12.2 km/hr or 7.6 mph, and it seems that the wind is less energetic in summer than in winter, by a factor of about 2 to 1.

If a WTG with a rated wind speed of 25 km/hr (15.5 mph) were installed, the rated windspeed would be exceeded about 10% of the time, particularly in winter, but the generator would typically deliver only about a quarter of its rated power, the exact figure depending on the turbine blade control system. This sort of operation will clearly pose generator-economics problems.



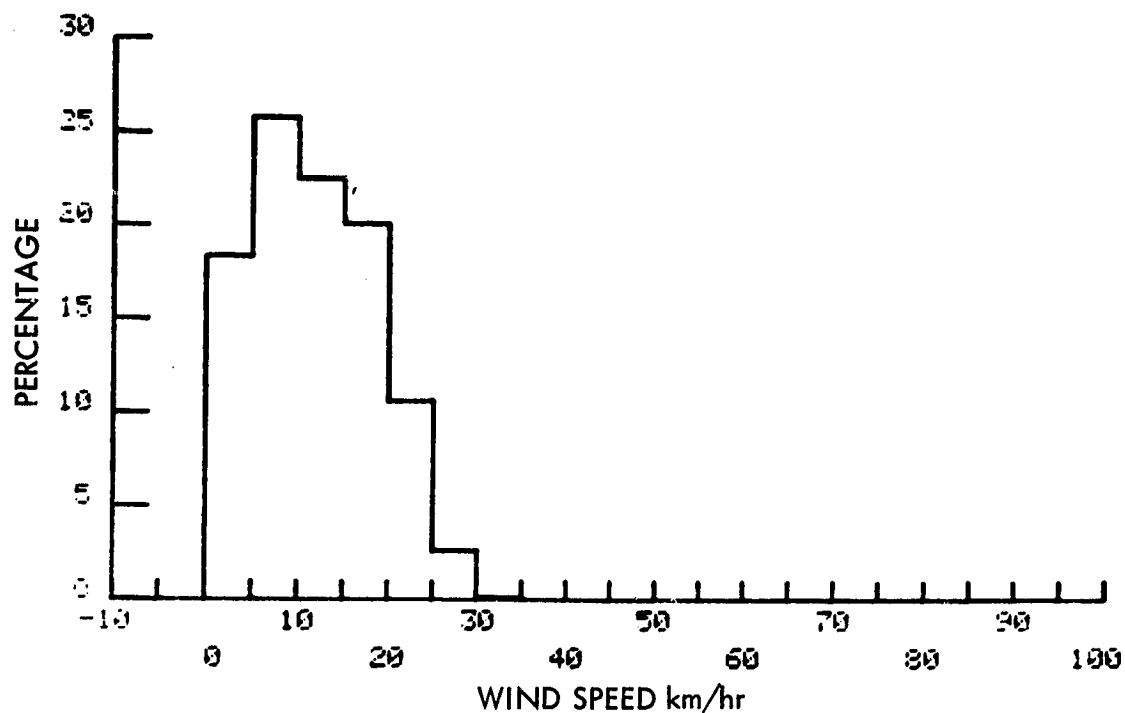
START: 79/01/01/00/00 END: 79/04/01/00/00

RANGE:		POPULATION:	
SAMPLES:	8144	SAMPLES:	8144
MEDIAN:	14.488	MEDIAN:	14.488
MEAN:	15.752	MEAN:	15.752
STD DEV:	9.989	STD DEV:	9.989

CLASS	BOUNDARIES		SAMPLES	RANGE		POPULATION	
	LOWER	UPPER		PERCENT	CUM.	PERCENT	CUM.
UNDER	-10.00	-10.01	0	.00	.000	.00	.000
1	-5.00*	-5.01	281	3.45	.035	3.45	.035
2	0.00	4.99	783	9.61	.131	9.61	.131
3	5.00	9.99	1703	20.91	.340	20.91	.340
4	10.00	14.99	1454	17.85	.518	17.85	.518
5	15.00	19.99	1266	15.55	.674	15.55	.674
6	20.00	24.99	1114	13.68	.811	13.68	.811
7	25.00	29.99	781	9.59	.906	9.59	.906
8	30.00	34.99	454	5.57	.962	5.57	.962
9	35.00	39.99	215	2.64	.989	2.64	.989
10	40.00	44.99	70	.86	.997	.86	.997
11	45.00	49.99	13	.16	.999	.16	.999
12	50.00	54.99	2	.02	.999	.02	.999
13	55.00	59.99	3	.04	.999	.04	.999
14	60.00	64.99	3	.04	1.000	.04	1.000
15	65.00	69.99	0	.00	1.000	.00	1.000
16	70.00	74.99	0	.00	1.000	.00	1.000
17	75.00	79.99	0	.00	1.000	.00	1.000
18	80.00	84.99	1	.01	1.000	.01	1.000
19	85.00	89.99	0	.00	1.000	.00	1.000
20	90.00	94.99	0	.00	1.000	.00	1.000
21	95.00	99.99	1	.01	1.000	.01	1.000
OVER	100.00		0			.00	1.000

*NEGATIVE APPARENT WIND SPEEDS ARE CAUSED BY INSTRUMENTATION BIAS

Figure 3-1. Wind Histogram and Cumulative Distribution Data:
An Indiana Site, First Quarter, '79.
(Courtesy: AEP)



START: 79/04/01/00/00

END: 79/07/01/00/00

RANGE:

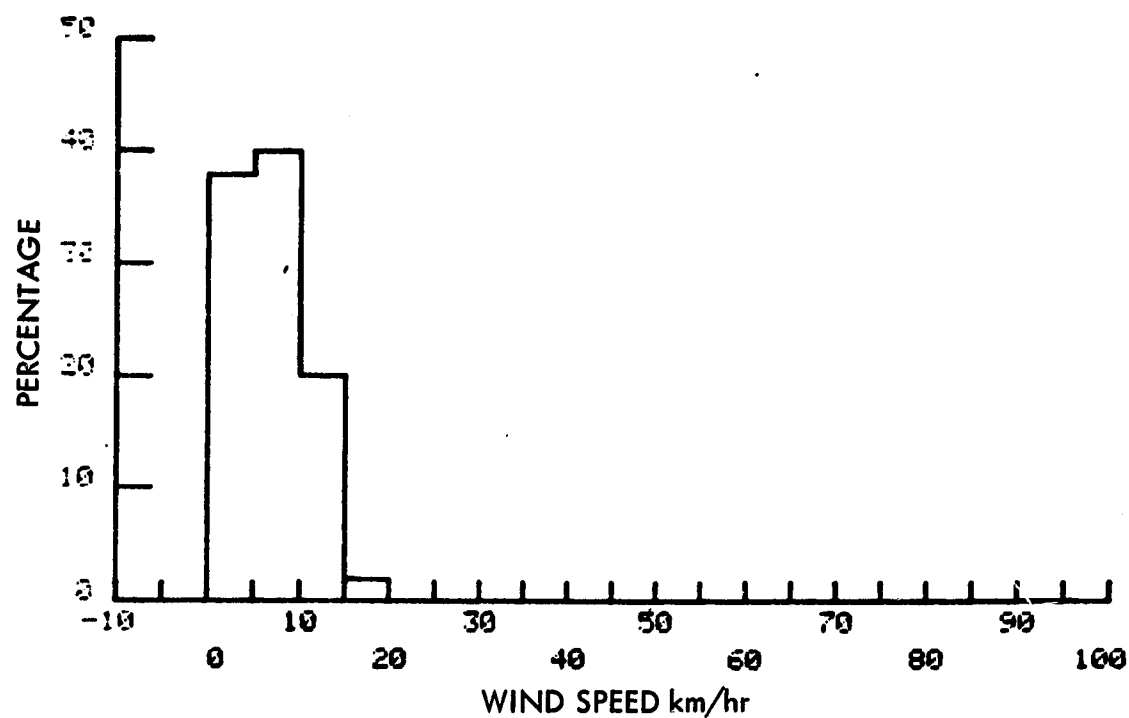
SAMPLES: 12238
 MEDIAN: 11.314
 MEAN: 11.817
 STD DEV: 6.704

POPULATION:

SAMPLES: 12238
 MEDIAN: 11.314
 MEAN: 11.817
 STD DEV: 6.704

CLASS	BOUNDARIES		SAMPLES	RANGE		POPULATION	
	LOWER	UPPER		PERCENT	CUM.	PERCENT	CUM.
UNDER		-10.01	0		.00		.000
1	-5.00	-5.01	0	.00	.000	.00	.000
2	-5.00	-5.01	0	.00	.000	.00	.000
3	5.00	4.99	2239	10.30	.183	10.30	.183
4	5.00	9.99	3157	25.80	.441	25.80	.441
5	10.00	14.99	2752	22.49	.666	22.49	.666
6	15.00	19.99	2452	20.04	.866	20.04	.866
7	20.00	24.99	1301	10.63	.972	10.63	.972
8	25.00	29.99	320	2.61	.999	2.61	.999
9	30.00	34.99	17	.14	1.000	.14	1.000
10	35.00	39.99	0	.00	1.000	.00	1.000
11	40.00	44.99	0	.00	1.000	.00	1.000
12	45.00	49.99	0	.00	1.000	.00	1.000
13	50.00	54.99	0	.00	1.000	.00	1.000
14	55.00	59.99	0	.00	1.000	.00	1.000
15	60.00	64.99	0	.00	1.000	.00	1.000
16	65.00	69.99	0	.00	1.000	.00	1.000
17	70.00	74.99	0	.00	1.000	.00	1.000
18	75.00	79.99	0	.00	1.000	.00	1.000
19	80.00	84.99	0	.00	1.000	.00	1.000
20	85.00	89.99	0	.00	1.000	.00	1.000
21	90.00	94.99	0	.00	1.000	.00	1.000
22	95.00	99.99	0	.00	1.000	.00	1.000
OVER	100.00		0		.00		1.000

Figure 3-2. Wind Histogram and Cumulative Distribution Data:
 An Indiana Site, 2nd quarter, 1979.
 (Courtesy: AEP)

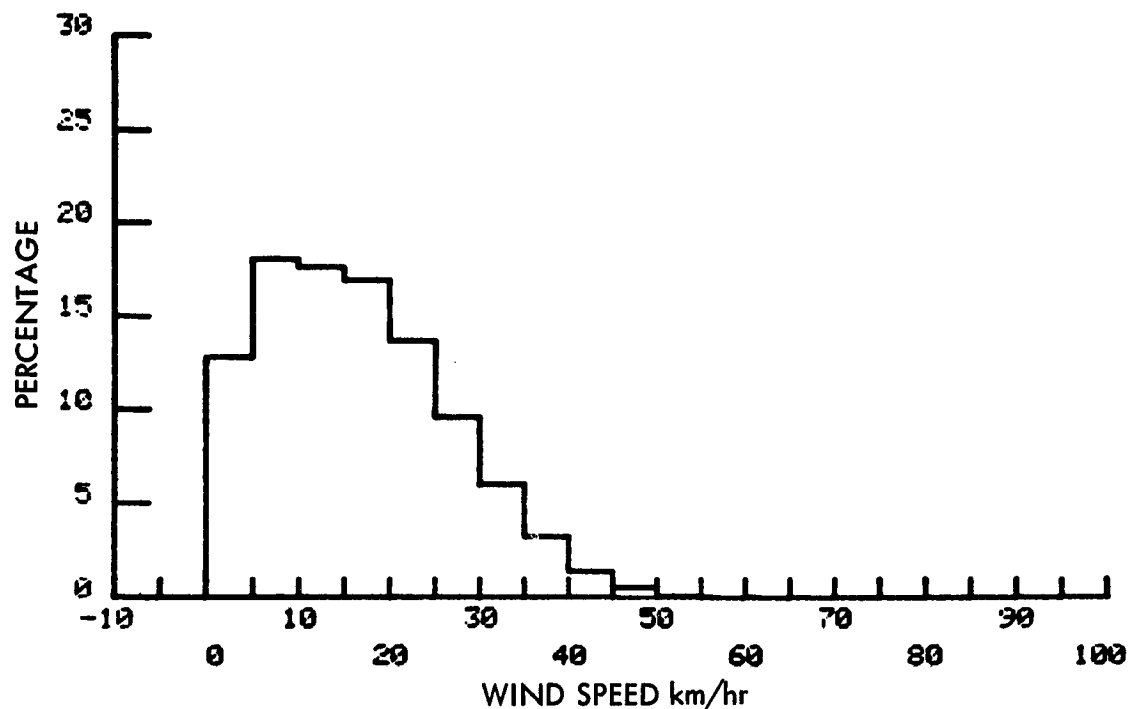


START: 79/07/01/00/00 END: 79/10/01/00/00

RANGE:		POPULATION:	
SAMPLES:	10574	SAMPLES:	10580
MEDIAN:	6.512	MEDIAN:	6.516
MEAN:	6.770	MEAN:	6.828
STD DEV:	4.460	STD DEV:	5.071

CLASS	BOUNDARIES		SAMPLES	RANGE		POPULATION	
	LOWER	UPPER		PERCENT	CUM.	PERCENT	CUM.
UNDER		-10.01	0			.00	.000
1	-10.00	-5.01	0	.00	.000	.00	.000
2	-5.00	0.01	0	.00	.000	.00	.000
3	0.00	4.99	4008	37.90	.379	37.88	.379
4	5.00	9.99	4229	39.99	.779	39.97	.779
5	10.00	14.99	2122	20.07	.980	20.06	.979
6	15.00	19.99	201	1.90	.999	1.90	.998
7	20.00	24.99	2	.02	.999	.02	.998
8	25.00	29.99	0	.00	.999	.00	.998
9	30.00	34.99	0	.00	.999	.00	.998
10	35.00	39.99	0	.00	.999	.00	.998
11	40.00	44.99	0	.00	.999	.00	.998
12	45.00	49.99	0	.00	.999	.00	.998
13	50.00	54.99	1	.01	.999	.01	.998
14	55.00	59.99	1	.01	.999	.01	.998
15	60.00	64.99	1	.01	.999	.01	.999
16	65.00	69.99	3	.03	.999	.03	.999
17	70.00	74.99	1	.01	1.000	.01	.999
18	75.00	79.99	1	.01	1.000	.01	.999
19	80.00	84.99	1	.01	1.000	.01	.999
20	85.00	89.99	3	.03	1.000	.03	.999
21	90.00	94.99	0	.00	1.000	.00	.999
22	95.00	99.99	0	.00	1.000	.00	.999
OVER	100.00		6			.06	1.000

Figure 3-3. Wind Histogram and Cumulative Distribution Data:
An Indiana Site, 3rd quarter, 1979.
(Courtesy: AEP)



START: 79/10/01/00/00

END: 80/01/01/00/00

RANGE:

SAMPLES: 10696
 MEDIAN: 15.444
 MEAN: 16.594
 STD DEV: 10.140

POPULATION:

SAMPLES: 10696
 MEDIAN: 15.444
 MEAN: 16.594
 STD DEV: 10.140

CLASS	BOUNDARIES		SAMPLES	RANGE		POPULATION	
	LOWER	UPPER		PERCENT	CUM.	PERCENT	CUM.
UNDER		-10.01	0			.00	.000
1	-10.00	-5.01	0	.00	.000	.00	.000
2	-5.00	-1.01	0	.00	.000	.00	.000
3	0.00	4.99	1373	12.84	.128	12.84	.128
4	5.00	9.99	1929	18.03	.309	18.03	.309
5	10.00	14.99	1885	17.62	.485	17.62	.485
6	15.00	19.99	1815	16.97	.655	16.97	.655
7	20.00	24.99	1469	13.73	.792	13.73	.792
8	25.00	29.99	1026	9.59	.888	9.59	.888
9	30.00	34.99	640	5.99	.948	5.99	.948
10	35.00	39.99	343	3.21	.980	3.21	.980
11	40.00	44.99	151	1.41	.994	1.41	.994
12	45.00	49.99	59	.55	.999	.55	.999
13	50.00	54.99	6	.06	1.000	.06	1.000
14	55.00	59.99	0	.00	1.000	.00	1.000
15	60.00	64.99	0	.00	1.000	.00	1.000
16	65.00	69.99	0	.00	1.000	.00	1.000
17	70.00	74.99	0	.00	1.000	.00	1.000
18	75.00	79.99	0	.00	1.000	.00	1.000
19	80.00	84.99	0	.00	1.000	.00	1.000
20	85.00	89.99	0	.00	1.000	.00	1.000
21	90.00	94.99	0	.00	1.000	.00	1.000
22	95.00	99.99	0	.00	1.000	.00	1.000
OVER	100.00		0			.00	1.000

Figure 3-4. Wind Histogram and Cumulative Distribution Data:
 An Indiana Site, 4th quarter, 1979.
 (Courtesy: AEP)

The basic problem to be solved by "power processing" for a wind turbine generator is the conversion of mechanical energy into electrical, at more or less constant voltage and frequency. The task is more difficult by the generally fluctuating nature of wind.

If an ac synchronous generator is used, it will usually be necessary to provide a gearbox to increase the generator shaft speed to a suitable value for a synchronous 60 Hz machine. Assuming that the problems of automatic synchronizing can be solved,* variations in wind speed would result in variations in power delivered to the system. Broadly speaking, there would be no problem remaining synchronized to the system - the torque angle of the generator would naturally adjust itself as the mechanical power input varied with the wind. Provided the receiving system were large enough, unmonitored operation in gusty conditions should be quite possible.

However, if the WTG system is a large part of the total system, or if a more controlled flow of power is needed, there may be some benefit to using a dc system rather than ac. If a dc generator is used, or if a rectifier system converts the output of an ac machine to dc, problems of synchronization and frequency control disappear. It could be arranged, for example, that variations in wind speed resulted in variations in the voltage of the (intermediate) dc system. It would then be a question of design whether such voltage changes resulted in variations in power delivered to the ac system or not. Within limits, the inverter would be arranged to supply constant power or constant voltage, or some intermediate characteristic could be chosen, the choice being determined mostly by the characteristics of the receiving system.

The use of a dc stage ahead of the ac system allows increased operational flexibility - the WTG shaft does not have to rotate at constant speed. This flexibility is bought, however, at the cost of additional power processing equipment and a reduction in efficiency, which implies a larger turbine for the same delivered power.

An even more complex system employing storage batteries may have merit in applications where a more constant source of energy is required or where the load may not correlate with the WTG output. With a battery system, wind energy can be used to charge the batteries when the load on the system is smaller than the wind-power potential, and the batteries can be used to supply the system load in the event that the wind decreases at a time of high demand. In addition, the batteries provide a sort of electrical inertia, so that the effects of short term wind gusts do not appear on the electrical system.

*Synchronizing requires that the generator and the remainder of the system be operating at the same frequency and with no phase difference, and that the voltage of each phase at the point of connection be the same on the system side and the generator side of the breaker.

Operation of WTGs will also have environmental effects. In addition to visual impacts, wind generators can create local radio and TV interference. These effects would tend to be minimized in areas where there are fewer people, suggesting that rural areas might be preferable sites for wind generators.

Another consideration unique to wind turbines is their impact on bird migrations. The Pennsylvania site was located in the center of the North American Flyway, which is a major migratory route for many species of birds. Impact on migrating birds could be lessened by installing the wind system in areas of the United States where migratory travel is less prevalent.

Many of the issues discussed above will affect the capital cost and economic viability of wind systems. If the land is already graded, or if batteries and data gathering equipment are not used, the capital cost of the wind system will be reduced. If the generator is located in a windy area, this will increase the electricity output, and the energy savings which will accrue to the owner. Land costs may be reduced by purchasing land in relatively low cost areas; this suggests that nonurban areas are more promising than urban ones for cost reasons as well as for environmental considerations.

However, all of these issues are tempered by public acceptance. Many of the factors listed above suggest that open rural sites would be among the most viable for installing wind turbine generators. However, if installation of these generators competed for scarce agricultural or range land, or if safety hazards to the surrounding community are involved, these problems may reduce public acceptance and the usage of wind generators.

b. Photovoltaics. A slightly different set of issues are important in the photovoltaic case. The main considerations here are power processing, annual weather conditions, environmental impacts, cost reduction, and public acceptance.

As with wind generators, the solar resource (insolation) is site specific. The insolation reaching the earth tends to be greater at lower latitudes. However, annual weather conditions are also important at any given latitude; usable direct radiation is significantly affected by the density and duration of cloud cover. Figure 3-5 illustrates how the availability of direct solar radiation varies across the United States. Insolation levels are higher in the southern latitudes, but they are also higher in the western regions, because of the reduced occurrence of cloud cover. (However, it may be noted that, broadly speaking, the amount of solar energy reaching the surface has a range of less than three to one over the continental United States.) In addition to these global effects, local geographic conditions such as altitude, pollution levels and the prevalence of dust storms will also change output from a solar facility. This suggests that a careful study of each potential site to determine insolation levels and factors which may reduce these levels will be useful when choosing a location and establishing the rating for a photovoltaic installation.

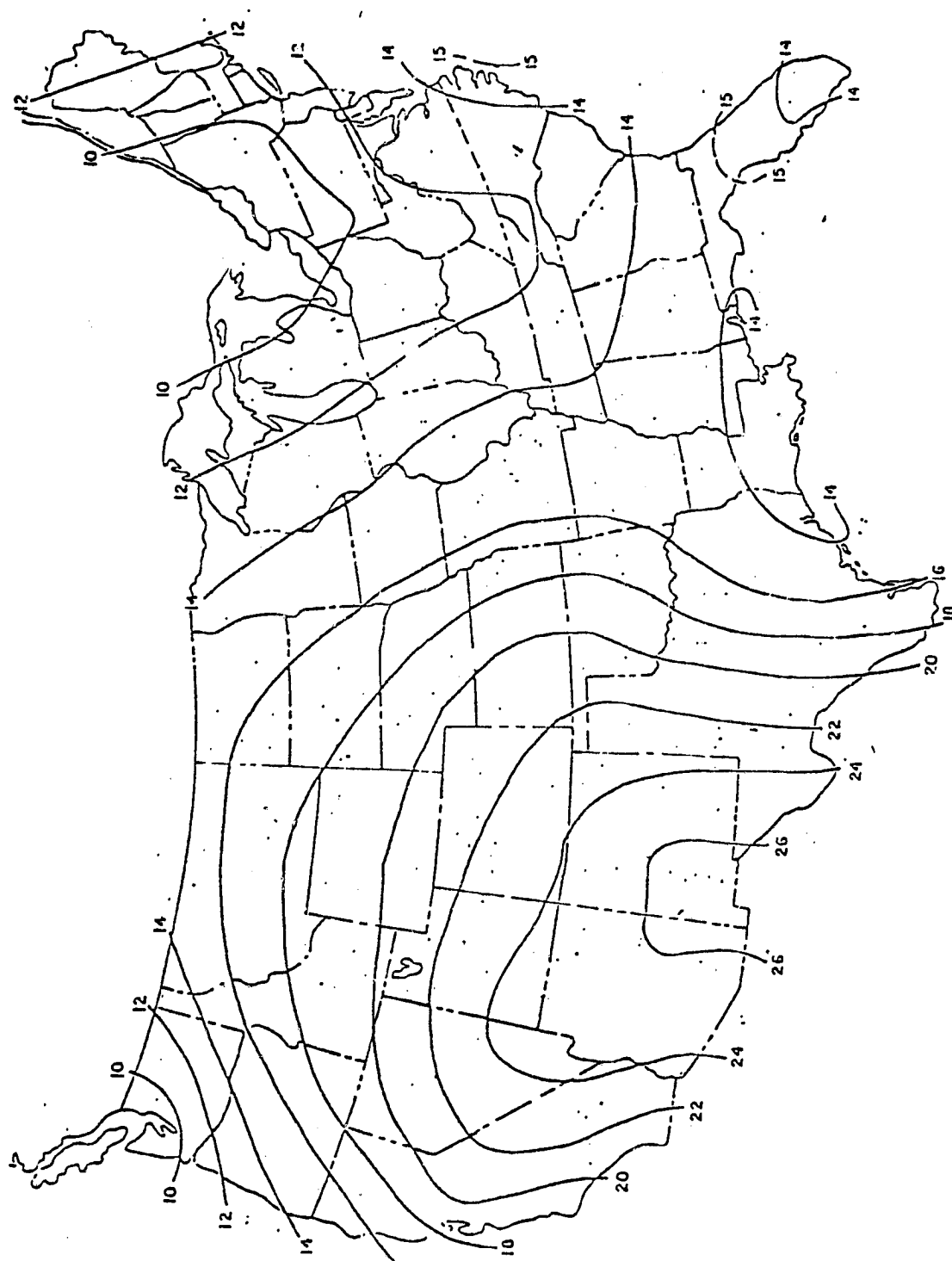


Figure 3-5. Average* Daily Direct Solar Radiation for United States (Megajoules/m²)
(Source: Courtest Air Resources Laboratory)

*Average over one year.

Environmental considerations will also be important when evaluating photovoltaics, and for PV environmental impacts occur in both directions. If large percentages of high-insolation areas are covered by PV cells, this may disrupt wildlife patterns. Conversely, local weather conditions will have an impact on PV energy production. Intermittent rainfall may reduce the need for panel cleaning; on the other hand, duststorms, high winds and other severe weather conditions may increase the need for maintenance and repair, or reduce the output of the PV system.

While location and environmental impacts are important determinants of usable solar radiation, cost reductions in the PV installation will be critical to the economic viability of photovoltaic energy production. The current prices for which PV cells can be produced are not competitive with the alternatives. However, innovations in the production process and cost savings through mass production may allow PV to compete with the alternatives, especially if the cost of other energy resources continues to rise rapidly. Another possible source of reduced costs is in the site preparation. If minimal changes in the site need to be undertaken to install PV cells, this will also minimize initial capital costs.

A final consideration may be public acceptance. Photovoltaic cells are relatively quiet and unobtrusive forms of electricity production, especially if installed upon existing roofspace. These attributes will allow PV panels to be used in populous areas, where they will be more visible than other DSG systems. Current perceptions of PV energy generation are positive, but if capital costs remain high or safety and reliability problems appear, this may cause favorable public opinion to wane.

c. Cogeneration. For cogeneration, the technology is beyond the experimental stages, and in some areas the use of cogeneration is already economically viable. Thus, considerations centered upon economic and institutional problems rather than technical ones. The major issues for cogeneration were: availability of waste heat, contractual arrangements, local environmental regulations, and liability concerns.

When estimating the cogeneration potential of a site or industry, attention must be given to the quantity and quality of waste heat, as well as the willingness of that industry to enter into long-term cogeneration contracts. The pressure, temperature, and fluctuations of waste heat output will determine the size of a potential cogeneration system. However, many industries with large amounts of waste heat are not suitable for installing cogeneration if there is uncertainty in the longevity of the plant or its average output. If long-term commitments cannot be made, it may not be beneficial to install cogeneration systems.

The economic viability of cogeneration is strongly affected by the contractual arrangements made. In the Rohr cogeneration case, several of these arrangements (backup electricity for computer operations, and availability of fuel oil reserves) reduced operating uncertainty. Another contractual arrangement which is very important,

but was not directly addressed in this case, is the rate at which cogenerated electricity may be purchased from and resold to the utility. The whole subject of electricity repurchase or buy-back rates for small power producers is not yet well defined. Pending rulemaking procedures under Public Utilities Regulatory Policy Act (PURPA) will set guidelines for purchase and sales prices of electricity between small power producers and utilities, as well as back-up and stand-by agreements. Since the profitability of a cogeneration site will vary with the rates made available to the cogenerating facility, clarification of this rate issue will have important impacts on cogeneration as well as other DSG facilities.

A third issue is local environmental regulation. For the Rohr case, this cogeneration facility was the largest generation system which could be built without having to meet Air Pollution Control District standards. In the state of California, larger cogeneration facilities would not be able to use this exemption; in other states, this maximum generation constraint may not apply. Other regulations which may be important to cogeneration facilities will involve restrictions on fuel usage. If the use of certain fuels is restricted during pollution alerts or for conservation reasons, some cogeneration configurations may not be viable.

A final concern is that of liability. At the time our interviews were conducted, the utility was responsible for meter reading and maintenance, even though this involved special trips by utility personnel. Labor savings could be realized by allowing Rohr Industries to take care of meter reading procedures (and this was being considered at the time of the interviews). However, the legal issues arising from allowing industry personnel access to utility equipment require further clarification.

2. Implications for DSG Technologies in General

The preceding sections have summarized the information obtained from each case, and have extrapolated this information to similar applications in other sites. Broadly speaking, the problems associated with installing and operating an individual DSG were minimal. If the penetration levels of dispersed technologies continue to be low, the issues raised in these sections would encompass most of the problems a potential DSG user would face. However, if the percentage of energy production served by DSG systems becomes significant, additional problems may appear. It may be relatively easy for the first DSG units to fit into existing generating patterns, but higher concentrations of DSG technologies may make issues out of impacts that went unnoticed at lower penetrations levels. These possible issues are addressed in the next sections, and follow the format of Tables 3-1 to 3-4. A word of caution should be placed here: since these conclusions are predictions rather than current issues, the information presented in the following subsections must be used with some care.

a. Technical Issues. It is clear from the three cases studied here that no significant technical problems remain unsolved for these DSGs. There seems to be no reason why this conclusion cannot be extrapolated to other DSG technologies. The implication, of course, is that the technology is well-enough developed to make the proper design decisions concerning the use of storage, type of inverter, grounding, protection system, and so on.

As long as dispersed storage and generation constitute a small percentage of the capacity of the utility system*, they will have negligible impact on the operation of that system. The reason for this is quite simple: the variability in load in a power system is so great from moment to moment, and so unpredictable that the addition of dispersed storage and generation in quantities small enough so as not to significantly affect the already present variations will not affect the utilities need for capacity in terms of its generation, transmission, or distribution systems.

In the event that a large number of low-power installations is put onto the distribution system, it is conceivable that the additional workload of maintenance might be prohibitive from the utility point-of-view. If so, with this in mind it is clearly important that low-power installations, if they are to proliferate under the ownership and operation of an electric utility, must be extremely reliable. The lack of availability of the power from a small percentage of "down" installations may not be important to the utility, but if it requires a crew to maintain the DSG installations, the additional cost must be charged against the value of the dispersed-generation electricity. It may be preferable, from the utilities point-of-view, to come to an arrangement with the customer whereby the latter owns and is responsible for maintenance on the dispersed storage or generation equipment.

With larger equipment, such as the 800-kilowatt cogeneration installation, or with concentration of smaller units on a feeder, the amount of generation would have a significant impact on a particular distribution feeder. The impact of such a large amount of generation would affect the design and construction of the distribution system, including its protection as well as the normal operation of the distribution network.

In general, dispersed generation sources are presently required to shut down when the incoming AC from the utility system is removed. There would seem to be no obvious reason, however, why a distributed generator, whether it be solar, wind, or a gas turbine, could not continue to supply an "internal" load in the event that the basic

*A figure of 10% is presently being used as a rule-of-thumb for the percentage penetration below which DSG impacts on operation may be considered negligible.

supply failed. Indeed, this is the case in the cogeneration at the Rohr plant. There are interesting problems to be solved in terms of the local controllers for the generators, and in terms of utility personnel protection and automatic re-synchronizing, but these are by no means unsolvable.

Evidently, then, the use of dispersed storage and generation can increase the apparent availability of electricity supply for the customer without adversely affecting the operation of the utility. Not until a large amount of dispersed generation is installed is the existence of such generation likely to be a significant factor in the operation of the utility system.

Another issue related to system operation is power processing. In two of the three cases studied here, the generation of electricity involved the use of a DC to AC inverter. The operation of such an inverter is dependent upon the generation of a string of firing pulses for the SCRs which comprise the inverter. The angle at which the SCRs are fired, with respect to the line voltage, controls the voltage from the inverter and the power factor at which the inverter operates, and the accuracy with which the control system can generate regularly spaced pulses determines to some extent the harmonic content of the output voltage. The control system will normally be designed to operate the inverter within a region of safe current and voltage limits up to the maximum power of the system. It is common practice in inverters to bias the operating point towards minimum extinction angle (corresponding to minimum VAR consumption on the inverter) although this is not strictly essential.

The exact design details of the control systems for these DC to AC inverters need not concern us here. The essential point is that each inverter control system can operate with only local information being required. No knowledge of the state of the remainder of the utility system is required for proper operation of the inverters.

A similar situation exists with the 800-kW cogeneration facility of San Diego Gas & Electric. Gas turbine controls can generally bring up a generator and synchronize it without any information about the state of the utility system. All that is required, as with the DC inverters, is a connection to an energized part of the distribution network.

It is thus seen that each of the dispersed generation techniques can be operated independently of much of the electric utility system to which they are connected. However, it would be misleading to create the impression that this situation is permanent or even desirable. At present, the utilities involved are being furnished with more information from the remote generation than is strictly necessary for its safe operation. These data will enable the utilities concerned to gain experience in the operation and application of the dispersed generation sources, and are essentially part of the experimental nature of the present installations.

However, the information thus provided may be used in the future in a hierarchical control system which uses the dispersed generation to enable the utility to achieve some particular objectives on its distribution system. The design of such hierarchical control system is described by Bahrami and Caldwell (Reference 40). A five-level monitoring and control system is described. Figure 3-6 shows a conceptual diagram of such a system.

At present, the amount of dispersed generation is so small that any attempt to control it so as to modify power line flows, or impact the system voltage, would probably be futile. However, as the amount of dispersed generation at any given feeder or distribution system increases, the usefulness of being able to control it increases and it is probably inevitable that control will be applied to DSG in the distribution network.

Since in the case of the wind turbine generator and the solar cell array the primary energy source is essentially free, it is likely that these generators will be controlled for maximum output at all times, although whether this energy goes into the utility system (and/or the load) or into local storage will be a decision made by the utility in the light of its immediate and anticipated needs. Interestingly, both wind and insolation in many areas tend to show daily variations not unlike a typical utility load curve.

The implementation of a control system (whether of five levels of hierarchy or less) aimed at the system-wide management and coordination of distributed sources of generation will require additional communications capability at the various levels.*

b. Cost Components. The emphasis placed on cost categories listed in Table 3-2 may change over time. Experimental technologies may focus upon special equipment for data acquisition and system safety during the initial design phase. However, as the technology matures, emphasis will shift to the financial considerations used in choosing among investments--initial and recurrent costs, and how these compare with alternatives. System costs may be unimportant for experimental units, but the long-term usage of individual DSG systems will depend upon their ability to compete with the expense and reliability of using other generation or storage technologies.

c. Environmental Issues. The environmental impact a DSG system will have varies with the technology. However, environmental impacts of DSG systems are definitely a function of their penetration levels. A single DSG system may have negligible impact on the environment, whereas widespread usage of the system may require large amounts of land, competing with residential or agricultural uses. A single wind turbine generator may be scenic, but a field of them may create an undesirable

*The requirements for each additional communication are the subject of another study (Reference: GE Study on monitoring and control requirement for DSG).

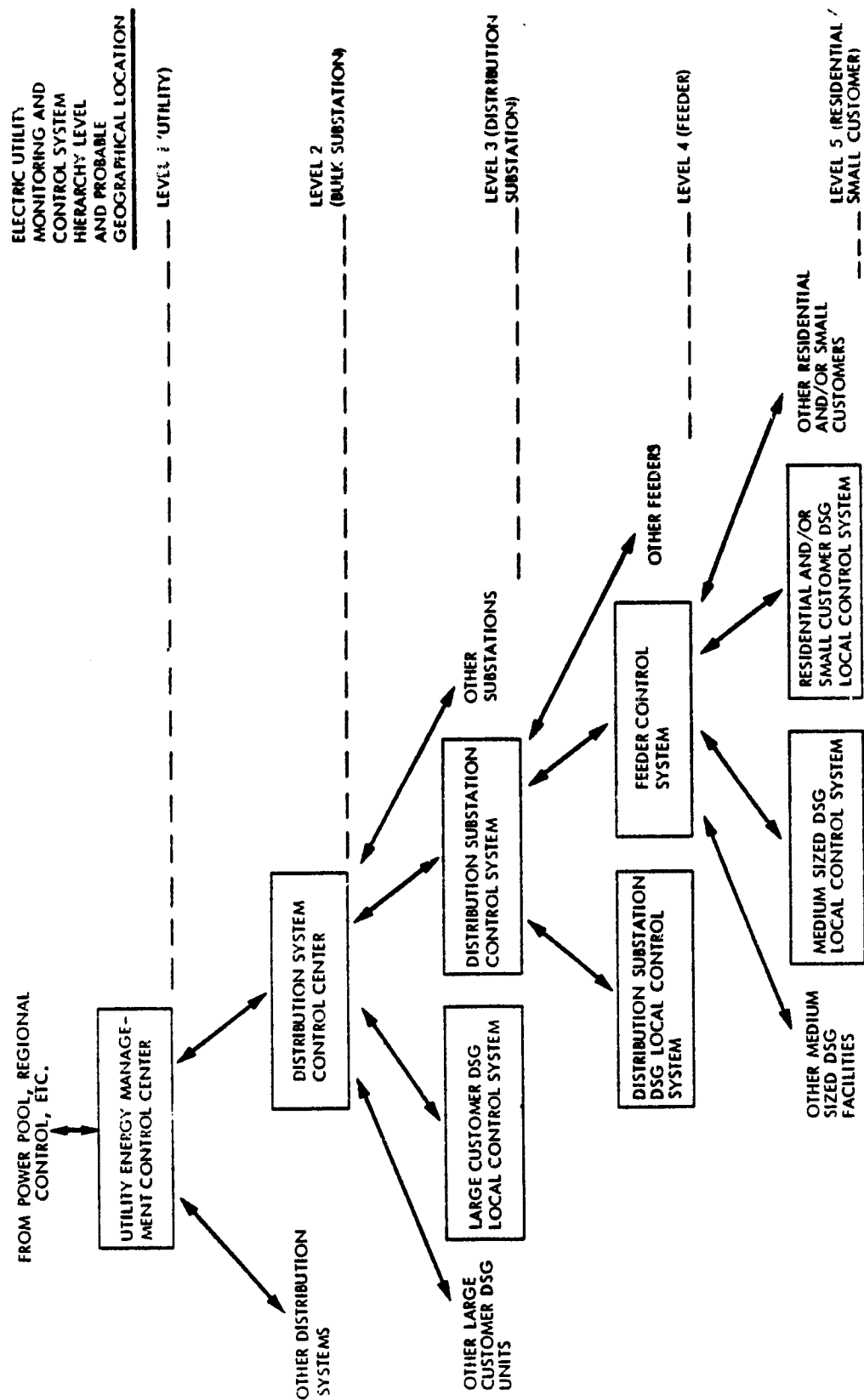


Figure 3-6. A Conceptual Diagram for the Monitoring and Control System for a DSG-Equipped Distribution System

amount of TV interference. An issue which was not addressed in this case study is the problem of waste disposal. Some of the new DSG technologies under consideration use significant amounts of toxic substances. For example, second generation solar cells may use cadmium sulfide or gallium arsenide rather than silicon. At the end of system lifetime of these DSG technologies, some provision must be made for the disposal of these substances.

d. Economic/Institutional Issues. A number of safety and liability considerations become issues when the DSG technology is jointly owned or operated by a utility and a small power producer. The legal issues at stake vary according to ownership arrangements. If the utility owns the system, it may be liable for any damages or injuries caused by the DSG system. Thus, even though it may be less costly for the user to maintain and operate the system, liability considerations prevent this arrangement from occurring at the present time. Conversely, if the user owns and operates the system, utility personnel and equipment must be protected from energy produced by the user. Currently, these issues are resolved on a case by case basis by the parties involved.

A number of regulations may become more prominent as DSG systems become more widely used. Zoning laws may become more strict if safety hazards appear in some DSG systems. Installation of a DSG system will probably require the user to prepare an environmental impact statement. A potentially important regulation, which is presently in the hearing stage, will govern the rate structures which apply to small power producers (Section 210 of the Public Utility Regulatory Policy Act). This regulation will set guidelines for agreements to purchase and sell electricity between small power producers and the local electric utility. If these rate structures become standardized, it will be much easier for small generation facilities to connect to local utilities. If tax credits or subsidies are given to small power producing facilities, these tax incentives will encourage adoption of DSG systems.

As stated earlier, another institutional consideration is public acceptance. Favorable perceptions of solar energy and cogeneration have supported the development of these DSG technologies. However, if some of these technologies require large amounts of desirable land, or have safety hazards associated with them, future public acceptance may subside.

A final possible issue is that of infrastructure. The current case studies represent very small quantities of generation. Thus, they have equally small impacts on the utility. However, if figure DSG systems represent a significant portion of generation, utilities may focus upon transmission and distribution services more than at present, in comparison to generation, and reorganize their capital mix accordingly. DSG systems will also require maintenance and meter reading services. It is not clear at this time whether utility personnel, or new independent businesses, will handle these services.

C. SUMMARY AND CONCLUSIONS

For a wide variety of reasons - rapidly rising fuel costs, environmental and safety issues associated with coal and nuclear power, availability problems with oil and natural gas, escalating capital costs associated with siting and construction of conventional generating facilities, increased uncertainty of energy supply - there has been a growing interest in the development and usage of dispersed storage and generation (DSG). This study focused upon three of the many possible DSG technologies, in an attempt to define the issues which are associated with these DSG technologies and their interconnection with local utilities, and to use this information to suggest issues which may need to be addressed in other DSG applications.

The three DSG cases studied were: a 45 kW wind turbine generator, built by Pennsylvania Power and Light Company and installed in Harwood, Pennsylvania; a 60 kW photovoltaic system located at Mt. Laguna Air Force Base in Mt. Laguna, California; and an 800 kW cogeneration system located at Rohr Industries in San Diego, California, and operated by Applied Energy, Incorporated, a subsidiary of the San Diego Gas and Electric Company. Each of these systems is described in detail in Part II of this document, which includes connection, site, construction, installation, operation, cost, and control information.

From the information presented in Part II, a list of the technical, economic, environmental, and institutional issues which will face future DSG systems was developed. Not all of the issues listed in Tables 3-1 through 3-4 were issues for these three cases, because of the experimental nature of these DSG technologies and because of the low levels of DSG penetration. If penetration levels remain low, only the issues outlined in Section III-B will be pertinent to the installation of similar DSG technologies in other applications. For wind systems, these issues are: resource availability, site selection, power processing, environmental considerations, impacts on bird migration, capital costs, and public acceptance. The main considerations for photovoltaics are annual weather conditions, environmental impacts, cost reduction, and public acceptance. Since cogeneration is beyond the experimental stages, the major issues are availability of waste heat, contractual arrangements, local environmental regulations, and liability concerns.

At the present time, because of their small number and small capacity, dispersed storage and generation installations have had a negligible effect on the operation of utilities. However, higher concentrations of DSG technologies may make issues out of impacts that went unnoticed at lower penetration levels. These possible issues are addressed in the final portion of Part III, and include:

- Technical Considerations - While the installation of a large number of small generators whose output is essentially uncontrolled (because it depends upon the sun or the wind) may not pose problems during the normal operation of the system, abnormal system conditions will almost certainly require some degree of monitoring and control capability. This capability will have benefits to the system in its

normal state (for example, the possibility of voltage control using DSG) but will impose a severe burden in the present communication and control system because of the large number of sources that a high penetration represents. Suitable control and communication methods and appropriate control strategies must be developed along with the DSG technologies.

- Pricing Agreements Between the User and the Utility - Currently, systems which are used jointly resolve contractual agreements on a case-by-case basis. However, pending rulemaking under PURPA will set guidelines for purchase and sales prices of electricity between small power producers and utilities, as well as back-up and stand-by agreements.
- Liability Considerations - Legal aspects of safety considerations become issues when a DSG technology is jointly owned or operated. These problems are currently resolved on a case-by-case basis.
- Regulations - Zoning laws may become more restrictive if safety hazards appear in some DSG systems, and environmental impact statements will be an integral prerequisite for non-experimental units.
- Waste Disposal - Some proposed DSG systems use toxic or hazardous materials to produce energy. Provisions must be made to safely dispose of these materials at the end of the substance or DSG system lifetime.
- Land Usage - Widespread adoption of DSG systems may compete with alternate land uses, such as, residential, recreational or agricultural purposes.

While the addition of some DSG systems may not be economically justifiable at present, a number of factors are increasing the costs of alternatives. In general, no unexpected problems were encountered in the planning, installing, commissioning, or operation of the dispersed generation systems studies here. However, some consideration must be given to impacts which may be significant if large numbers of DSG systems are used.

SECTION IV

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APPENDIX A

ECONOMIC METHODOLOGY AND ASSUMPTIONS

To compare investment options with differing capital costs and cash flow profiles, the dollars received and expended at various times need to be evaluated on a consistent basis. This is done through the use of life-cycle costing: all receipts and expenditures for each investment option are expressed in present-day dollars, so they may be aggregated into a single number. The aggregate number is a project's net present value (NPV), and it may be compared with the corresponding number for other investment options. A brief description of the NPV methodology is contained in Section I of this Appendix.

NPV is very sensitive to the assumptions made about system lifetime, discounting factors, buy-back rates, and cost escalations. Changing any of these assumptions may change the relative ranking of alternatives. Thus, one useful calculation is the break-even buy-back rate: it is the lowest price at which electricity (or steam, in the cogeneration case) must be sold for the dispersed system to be as attractive as the conventional one. These rates are calculated (where possible) in the main body of the report.

Since economic assumptions can have an important effect on NPV, Section II of this Appendix lists a standard set of assumptions which were used to analyze these case studies. The assumptions are probably not valid for all users or all situations. For this reason, the methodology is presented so that potential users may tailor it to their individual situation.

A. CALCULATING NET PRESENT VALUE

NPV is simply the difference between revenues and costs generated by the system under consideration, where all cash amounts are expressed in current dollars to make them comparable. The complexity of NPV formulas stems from including all costs (the initial investment, fuel expenses, O&M, etc.), adjusting for taxes, and translating each amount into present-day dollars. The basic formula for calculating the NPV of a system is:

NPV = The initial investment (denoted "K")

less: tax deductible depreciation

less: investment tax credits

plus: miscellaneous expenses

plus: electricity costs

plus: O&M costs

plus: fuel costs

less: receipts from sales of excess energy

Each of the terms in this equation is translated into a numerical formula below.

1. Tax Deductible Depreciation

This requires calculating a depreciation rate, multiplying the rate by K, the capital investment, to determine total depreciation, and

then multiplying total depreciation by the tax rate to derive the amount of deductible depreciation. Depreciation may be calculated in a number of ways, and involves the accounting lifetime of the system (denoted N_a) and the discount rate used by the firm (r). For straight-line depreciation methods,* the depreciation would be $1/N_a$ each year. Since depreciation accrues annually over the accounting life of the investment, the present day equivalent of such depreciation (D) may be expressed as:

$$D = \frac{1 - (1+r)^{-N_a}}{N_a \cdot r}$$

However, most private utilities, for tax purposes, use a depreciation rate which reflects the fact that an investment depreciates most rapidly in the initial years. The depreciation method used in this study is the sum-of-the-years-digits methods; it has a present day equivalent of:

$$D = \frac{2 \cdot [N_a - \frac{1 - (1+r)^{-N_a}}{r}]}{N_a \cdot (1+N_a) \cdot r}$$

Once a depreciation method is chosen, its present value (D) may be combined with the corporate tax rate (t_i) and the capital investment (K) to determine the tax deductible depreciation.

$$\text{tax deductible depreciation} = t_i \cdot D \cdot K$$

*This is used by most public utilities, and by many private utilities for regulatory or book value purposes.

2. Investment Tax Credits

If a tax credit for the new system exists, it reduces the tax burden by a factor t_c .

$$\text{investment tax credit} = t_c \cdot K$$

3. Miscellaneous Expenses

Other payments, such as property taxes and insurance premiums, may be approximated by a constant multiple (t_m) of the initial capital cost.

$$\text{miscellaneous expenses} = t_m \cdot K$$

4. Electricity, O&M, and Fuel Costs

These include all the recurrent costs associated with system operation throughout its lifetime (N_s). Since the various costs probably escalate at different rates, and none of these rates coincide with the discount rate, it will be necessary to escalate costs separately before discounting them to present-day dollars. If C_j represent annual costs and E_j is the escalation rate (the subscript j is a variable, representing electricity, O&M, or fuel costs) the general formula for recurrent costs is given below. The first term is the annual cost; the remainder of the right-hand side adjusts this cost into current dollars:

$$\text{Recurrent Costs} = C_j \cdot \frac{1 + E_j}{r - E_j} \cdot \left[1 - \left(\frac{1 + E_j}{1 + r} \right)^{N_s} \right]$$

(j = electricity, O&M, and fuels)

5. Receipts From Sales of Excess Energy

Each year, revenues from the sale of by-product power (electricity, steam, etc.) may be generated. These are calculated in a manner similar to recurrent costs, where R_j replaces C_j as the number to be adjusted to present day amounts. In later analysis, R_j will become a variable, to indicate what kinds of buy-back rates make dispersed system profitable.

$$\text{Receipts from sales} = R_j \cdot \frac{1 + E_j}{r - E_j} \cdot \left[1 - \left(\frac{1 + E_j}{1 + r} \right)^{N_s} \right]$$

(j = electricity, steam, etc.)

6. NPV Revisited

Having briefly explored the NPV methodology, it is useful to have the entire formula, and definitions of each variable, in one place. This is done below.

$$-NPV = K - t_i \cdot D \cdot K - t_c \cdot K + t_m \cdot K$$

$$+ C_e \cdot \frac{1+E_e}{r-E_e} \cdot \left[1 - \left(\frac{1+E_e}{1+r} \right)^{N_s} \right] + C_{O\&M} \cdot \frac{1+E_{O\&M}}{r-E_{O\&M}} \cdot \left[1 - \left(\frac{1+E_{O\&M}}{1+r} \right)^{N_s} \right]$$

$$+ C_f \cdot \frac{1+E_f}{r-E_f} \cdot \left[1 - \left(\frac{1+E_f}{1+r} \right)^{N_s} \right] - R_j \cdot \frac{1+E_j}{r-E_j} \cdot \left[1 - \left(\frac{1+E_j}{1+r} \right)^{N_s} \right]$$

where

C_e = annual electricity costs

C_f = annual fuel costs

$C_{O\&M}$ = annual O&M costs

D = depreciation rate

E_e = electricity escalation rate

E_f = fuel escalation rate

E_j = by-product power escalation rate

$E_{O\&M}$ = O&M escalation rate

K = initial capital investment

N_a = accounting lifetime of system

N_s = system lifetime

r discount rate

R_j = annual revenues from sales of by-product power

t_c = investment tax credit

t_i = income tax rate

t_m = miscellaneous expense rate

B. ASSUMPTIONS USED FOR COMPARATIVE ANALYSIS

Many of the values needed to calculate NPV - electricity, fuel, and O&M costs, the initial investment, system lifetime, and annual revenues - were obtained through company reports and interviews with personnel involved with the cases studied. These values are listed in

the main body of this report. However, additional information on general economic conditions is also needed; a description of these assumptions is outlined below.

- (1) Escalation Rates. Each cost and revenue category will increase over time, due to inflation as well as growth or scarcity conditions. While all categories may grow, each will do so at a different rate. Choosing appropriate growth rates is difficult, because so many assumptions are built into any forecast. Data Resources, Incorporated (DRI) has developed a set of energy and economic forecasts based upon its model of the U.S. economy. The assumptions used in the DRI model are considered reasonable, and are used in this study. Their forecasts of growth are made over 10-year intervals; thus, a project with a 20-year lifetime which began operation in 1978 would face one DRI escalation rate until 1980, another until 1990, and a third until the end of its lifespan in 1998. To "smooth" these escalation rates, a single rate is chosen which results in the same overall growth as the three separate ones. This single number is the escalation rate used in the main report.
- (2) Electricity Escalation Rate (E_e , E_j). While this rate reflects the growth in users utility bills (E_e), it should also approximate the growth in utility willingness to pay for surplus electric power (E_j). The "Average Industrial

Electricity Prices" of the DRI model* are expected to grow in the following manner over the next 20 years:

1979 - 1980	14.8%/yr.
1981 - 1990	7.9
1991 - 1998	6.9

During this period, a constant annual growth of 8.17% would give the same result. Thus, 8.2% is used as the electricity escalation rate.

- (3) O&M Escalation Rates ($E_{O\&M}$). A number of resources are used in the operating and maintaining of a generating system - labor, parts, water, chemicals, energy, etc. However, since a detailed breakdown of these components was unavailable, the "Adjusted Average Hourly Earnings" forecasts are used as a proxy for O&M growth. The changes listed by DRI* were:

1979 - 80	8.5%/yr.
1981 - 90	8.0
1991 - 98	7.3

This is equivalent to an annual rate of 7.8%.

- (4) Fuel Escalation Rates (E_f). The alternative fossil fuel varied with the case studied. The DRI rates* for coal,

*Source: Data Resources, Inc. Energy Review, Lexington, Mass., Vol. 3, No. 2, Summer, 1979.

oil, and natural gas and equivalent escalation rates are given below.

<u>Time Period</u>	<u>Coal</u>	<u>Oil</u>	<u>Natural Gas</u>
1979 - 80	11.4%/yr.	17.3%/yr.	16.5%/yr.
1981 - 90	10.1	11.9	15.4
1991 - 98	<u>8.2</u>	<u>9.2</u>	<u>9.7</u>
Average Rate	9.5%	11.3%	13.2%

- (5) System Lifetime (N_s). Although little evidence on length of operating life is available, a 20-year lifetime is assumed.
- (6) Accounting Lifetime (N_a). The capital investment is depreciated over a ten-year accounting life. If the accounting and system lifetimes were both assumed to be 20 years, the new investments would be less attractive economically than if accelerated depreciation is assumed.
- (7) Discount Rate (r). This represents the return a firm expects (after taxes) rather than the cost of capital, the expected return is assumed to be 15%.
- (8) Investment Tax Credit (t_c). To conform with current tax laws, a 10% investment credit on taxes is assumed.
- (9) Income Tax Rate (t_i). A combined state and federal tax rate of 50% is assumed for each case.
- (10) Miscellaneous Expense Rate (t_m). This includes property and other taxes as well as insurance premiums. It is

usually approximated by a percentage of the capital cost,
here, this is assumed to be 2.5%.

APPENDIX B
UTILITY INTERVIEWS

This Appendix is based upon notes taken during interviews with utility personnel, regarding the energy systems described in the main body of this document. Information in this Appendix follows the chronological order of the interviews; conclusions drawn from this information are presented in Sections II and III of this Report.

A. INTERVIEW AT PENNSYLVANIA POWER AND LIGHT (PP&L)

Participants

<u>PP&L</u>	<u>JPL</u>
J. E. Pfluger	K. A. Bahrami
R. P. Johnson	R. W. Caldwell

Date of Interview: July 9, 1979

1. DSG System Description

The wind generation system is located 3 miles west of Hazelton, Pennsylvania. The system connects to a 12-kV line near the Harwood Substation of PP&L.

The system consists of a wind turbine manufactured by T. Mehrkam of Energy Development Corporation, Hamburg, Pennsylvania. It has a four-blade rotor, which was apparently designed for operation at 37-40 rpm, however, there exists a blade resonance that can be excited near 40 rpm. The shaft of the rotor was designed to be connected to an AC generator through a 50-1 gear ratio gearbox; however, a 30-1 gear ratio gearbox is

now used. The speed of the rotor with this gearbox is 30-33 rpm. The AC Generator runs at approximately 1000-1200 rpm. The output of the AC Generator is rectified (full bridge) and is connected to fifteen 12-V (traction vehicle type) batteries. The output from the wind generator charges the battery system until the voltage of the batteries increases beyond (an adjustable) threshold. At that time the DC to AC inverter is connected to convert the wind power to AC 240, 3-phase and feed the utility distribution feeder through a bank of distribution transformers. The inverter used is a line commutated inverter, manufactured by Gemini, Cedarburg, Wisconsin.

The wind machine can operate at wind speeds of 7.5 - 35 mph. At speeds above 35 mph the machine is shut down. Wind speeds of up to 10 mph may be needed to start the turbine from standstill, however, wind speeds as low as 5 mph may be sufficient to sustain the rotation of blades once at speed.

The system is rated at 45 kW (continuous rating) which corresponds to a wind speed of 27 mph. The output is connected by 3 single-phase transformers (each rated at 25 kVA) to the 12-kV feeder.

2. Selection Process

Wind technology was selected based on the consideration that PP&L customers had installed, and were installing, wind machines. Since these were all of the same manufacture, PP&L decided to test the same device. If such customer-owned installations were to proliferate, the utility felt a natural need to understand the ramifications of

integration of such machines. A related motivation appeared to be a desire to become more knowledgeable about such machines and their characteristics than the customers.

A further reason given for selection of the Energy Development Company device was that, other than the blades and some packaging of controller devices, the components were "off-the-shelf."

3. Design and Construction

PP&L selected a site near Hazelton, Pennsylvania which many years ago was a generation site. This site was claimed by many people as being very windy. No quantitative wind data for that specific location was available. A great deal of effort (and the majority of the cost involved in the plant) was expended in site preparation; clearing trees; upgrading the access road, installing the wind turbine generator and foundation, erecting the prefabricated building to house the inverter, battery, switchgear and instrumentation, and fencing grounding, conduit and wiring.

The cost of equipment was 35-40k\$. Gemini's inverter was about 10k\$, wind turbine, control panel and rectifier were about 15k\$, batteries were about 5k\$, instrumentation/recording devices were about 5k\$. The total cost of the system including equipment, site preparation, etc. (i.e., the entire wind installation) was \$240,000. The primary cost was in site preparation, even though they (PP&L) already owned the land.

No particular skills (in addition to those that the utility engineering and construction crews already have were necessary for plant installation.

There are two brake systems. (1) Mechanical (which requires power to release) and (2) electric (up to 90 Vdc).

4. Start-up

The automatic yaw system periodically positions the WTG in the downwind direction. The electric brake is released automatically at wind speeds of approximately 6-8 mph. The WTG generator initially is connected only to the rectifier battery, and charges the battery to a predetermined level (based on cell voltage) prior to closure of a contractor which adds the inverter to the system. The main disconnect switch on the 240 V 3-phase AC entry is normally closed, providing the Gemini inverter with a synchronizing pulse.

5. Shutdown

When wind speeds decay to levels (about 5-7 mph) where the WTG output is insufficient to provide a net energy output from the system, the rectifier-WTG are disconnected from the system. The battery is then discharged through the inverter to the distribution system to a predetermined level. This assures the ability of the battery to accept a charge upon subsequent startup.

6. Plans, PV, Testing

The people at PP&L are thinking of adding Photovoltaic panels to the system at the same site. The rating under consideration is 7-15 kW or as much as 20 kW.

They are also planning to use the WTG AC Generator as an induction generator and directly feed power to the utility line (i.e., eliminate rectifiers and inverter). This requires going back to the original gearbox (i.e., 50-1 gear ratio). The generator speed will be 1800 rpm. It is recognized that if batteries are not used, then there may be some difficulty for synchronization and initial connection to the line. This is due to the fact that during gusty conditions the power output of the turbine generator may vary greatly and cause rapid changes in the generator shaft speed. One suggestion would be to use some controllable dummy loads during synchronization.

Provisions have been made for testing of a different inverter, with a transfer switch already installed. For testing during the next 2 years they have allocated 35k\$/year for O&M.

7. Problems

They have had these two problems:

- (1) With no preload on the machine, the turbine speed increased and (after the batteries were charged) the voltage on the DC bus increased above the AC triggering signal (AC from utility line) causing 2 SCRs to fire simultaneously, causing a dead short. This led to sudden stoppage of the wind turbine blade.
- (2) A control card failed, causing 2 SCRs to fire simultaneously causing a short, blowing a fuse in the inverter.

8. PP&L and Customer Owned Wind System

- (1) At present, PP&L will pay an amount equal to the average annual fossil fuel cost for customer generated power and fed to PP&L's system. In 1978, that amount was about 1.5¢/kWh.
- (2) PP&L requires a mechanism under PP&L control by which PP&L can completely (physically verifiable) disconnect the customer wind system from the PP&L system.

9. Control and Alarm

A radio control alarm system sends alarms to a nearby control center which may indicate any of the following four problems:

- (1) System shutdown due to either excessive or not enough wind.
- (2) Safety shutdown.
- (3) Loss of Station (separate line from utility) Power.
- (4) Inverter off.

B. PHOTOVOLTAICS SYSTEM AT MT. LAGUNA AIR FORCE STATION

<u>Participants</u>		
<u>Mt. Laguna</u>	<u>Delta Electronics</u>	<u>JPL</u>
Lt. M. E. Hatch	Larry Suelzle	K. Bahrami
R. Lewis		J. Stallkamp
A. Syverts		A. Walton

Date of Interview: August 21, 1979

Mount Laguna Air Force Station is a remote site 60 miles east of San Diego, located atop a 6,000-foot peak in the Cleveland National Forest. Approximately 200 civilian, military, and Federal Aviation Administration personnel operate the station and the radar installations. These radar facilities are scheduled to be turned over to the Federal Aviation Administration, and will be used jointly by the FAA and the air defense system for air traffic control and surveillance.

The Mount Laguna site was chosen for addition of PV for a number of reasons. It is a remote site: all electricity is produced at the station. Without solar energy, the monthly usage of electricity - about 500,000 kWh, with an average load of 750 kW - is met by burning 38,000 - 40,000 gallons of diesel fuel (11-12 kWh/gallon of diesel fuel). By using the 60-kW photovoltaic system, the station expects to save about 35 gallons of diesel fuel per day. Diesel fuel is purchased in 75,000 gallon lots, for about 73¢/gallon, there is also a 150,000 gallon storage capacity. Another reason for the choice was the high insolation levels Mt. Laguna receives. In addition to having a large number of clear days, it receives about 1100 W/m^2 of sunlight continuously, which is higher than most regions.

The photovoltaic system is located on a 170 ft x 190 ft site. There are two types of panels: 1610 Solar Power panels (46 in. x 15 in. each) and 756 Solarex panels (23 in. x 23 in. each). Output varies from 0-64 kW, with an overall efficiency from solar power to ac power output of order of 10-15%. The generated energy is used to provide about 10% of the station's daytime needs. Although solar insolation is intermittent, this was considered as not a problem, the PV system output changes slowly

compared to the radar loads. Mount Laguna had the plant installed by June 20, but only had about 200 hours of operating experience until August 15, when operation became continuous.

The power plant was installed in 1959, and consists of seven turbines - while three are in use, three are offline and one is undergoing maintenance. The system is completely manual, although there is an automatic synchronization feature for paralleling units. Maintenance is all done at the station by members of the staff.

The photovoltaic system costs \$1.6 million dollars, which was broken down as follows: (Partial approximate breakdown)

Solar Panels	\$1.1 million
Power processor	\$80K
Site preparation	
foundation &	
panel frames	\$140K
Paralleling and	
monitoring	\$25K
Non-recurring	
engineering	\$220K
Data acquisition computer (non-essential) supplied under separate contract	

This system is expected to have a lifetime of 20 years. It has only been operative for a short period of time, so maintenance requirements are unknown at this time. The first ten years are expected to be maintenance free, and later the possibility exists for purchasing a maintenance contract at a maximum of \$2000 per year.

Since the system has only been in continuous operation since August 15, little information exists on operating problems. One safety hazard mentioned was that if a faulty cell and the supportive frame were touched simultaneously, an electrical shock could result.

Delta Electronic Control Corporation located in Irvine, California has been responsible for: 1) the design and construction of the system, 2) testing and demonstration of the PV system connected to a SCE feeder during the early phases of the project, and, 3) the assembly and checkout of the entire system at the Mt. Laguna radar site.

The power processor consists of: 1) a DC voltage limiter, 2) a self-commutated inverter and, 3) controller (control logic). The controller performs 4 major functions:

- (1) Peak power tracking, i.e., to maximize the instantaneous power obtained from the array.
- (2) Monitoring of system parameters. This includes metering of both real and reactive power, and measurements of various voltages and currents.
- (3) Automatic shutdown and start-up (e.g., automatic start-up when power exceeds 6 kW, and automatic shutdown when it goes below 25 kW on a persisting basis).
- (4) Minimization of reactive power.

The power processor includes a contractor which constitutes the utility connect/disconnect device. The output of the PV plant feeds a 480V 3-phase feeder.

During the time the system was undergoing test at the Delta Electronics facility at Irvine, California, it was connected to the SCE system. A conventional circuit breaker served both as protection and lockable disconnect for the photovoltaic system. In this particular case, SCE did not require sole control over the disconnect. This might have been due to the temporary nature of the connection.

During the interview JPL learned that the cost of the power processor was about 1000 \$/kW, complete with controls. It was estimated that standard production units could cost 500 \$/kW initially. The cost could be reduced to 200 \$/kW for large volume production.

C. APPLIED ENERGY, INCORPORATION

Participants

AEI

C. Harmstead

P. Hodiak

JPL

J. Stallkamp

A. Walton

Date of Interview: July 5, 1979

Applied Energy, Incorporated (AEI) is a subsidiary of the San Diego Gas and Electric (SDG&E) Company. AEI handles all of SDG&E's cogeneration activities, but it is not organized to handle the purchase of industrially generated power. If the industrial firm wants to own the generation equipment, arrangements must be coordinated in the power contract with SDG&E.

The first topic of discussion was an historical overview of how the Rohr cogeneration system was adopted. Surprisingly, the initiative was not taken by either Rohr or SDG&E. In February of 1977, Archie Kelley

(then with ERDA) did some preliminary analysis to see if cogeneration could be used at Rohr. The results promised to be beneficial to all parties involved -- the new facility would meet the APCD standards that SDG&E faced, and would result in substantial dollar savings for Rohr. In September of 1977 a contract consisting of two consecutive ten-year terms involving Rohr, SDG&E, and AEI was signed. AEI was "on site" in February of 1978 with a brand new generating unit. But in April some lengthy switchgear delivery problems developed, delaying completion of the installation until mid-October. The unit was commercially operational in February of 1979.

Questions then centered upon AEI's operating arrangements. The turbine system belongs to SDG&E, but AEI is responsible for all operating, maintenance, and fuel costs. The site is approximately 30 ft x 80 ft, and contains a Saturn gas turbine capable of producing 800 kW of electrical output, and the engine was described as relatively small and quiet. Energy transactions between Rohr, AEI, and SDG&E are in a Btu or heat-rate related denomination rather than in dollars. AEI, and indirectly Rohr through its contract, buys exhaust heat from the turbines on this non-dollar basis. AEI also purchases No. 2 distillate oil and electricity for use in its operations for Rohr. The other cogeneration sites operated by AEI (steam supplied to the Navy) use natural gas in addition to oil. Any electricity produced by the turbines is fed back into the SDG&E grid, for which AEI receives an energy-denominated credit, these credits are used to offset AEI's turbine fuel purchases from SDG&E. Although Rohr buys electricity at time-of-use (TOU) rates, AEI's turbine is not charged nor credited as a peaker. Rohr also has a special tie-in arrangement with the cogeneration plant. In the event of a utility power

failure, electrical load will be transferred to the turbine generator. This would assure that Rohr's computer system — tape drives, cooling, and auxiliary lighting — continued to function at slightly reduced overall power. Rohr also has access to the diesel in AEI's supply tanks, and it repays AEI in kind.

The Rohr electrical capacity is about 6 MW at the Chula Vista complex. The plant is connected to SDG&E at the 12 kV distribution level, and this connection has no unusual characteristics. Rohr requires steam on a continuous 24 hr/day, 365 day/year basis. There are three work shifts per day, and Rohr equipment is kept operating at all times.

The operating arrangements used by all three parties involved are not considered hard-and-fast business agreements. This is a "test bed" facility, which is being used to test the viability of utility-owned industry cogeneration in return for possible downstream benefits. Rohr is the smallest of approximately thirty cogeneration applications that were considered, but larger installations would have had APCD offset problems.

Although members of AEI did not feel free to discuss the technical details, they did mention that some operating issues had arisen. They emphasized that the current arrangement was satisfactory, but that some contractual details would be reworked in future efforts. One such detail was monitoring. AEI currently visits the site near Rohr three times a day, although this arrangement will change next winter. If AEI could get Rohr to check out and operate the monitoring equipment, cogeneration activities would be cheaper for both of them.

Paul Hodiak was then asked about his future expectations for cogeneration. He felt that the majority of additional uses would be replacements for or supplements to existing facilities, because there is less uncertainty when the company is well established and the steam production process is known. Furthermore, the growth of generation capacity is constrained by a myriad of factors, including insufficient gas pressure, various regulatory agencies, and liability problems associated with access to the facility. Mr. Hodiak acknowledged that the California Public Utilities Commission (CPUC) has encouraged the use of new energy sources. But he also stated that AEI would exist and operate even without the encouragement from CPC.

Finally, the participants from AEI were asked about the prospects for non-utility owned cogeneration. Paul Hodiak felt that the prospects for third-party cogeneration were not encouraging.

APPENDIX C

PERTINENT PUBLISHED DATA

This Appendix includes the following:

- (1) Bahrami, K. A. and R. W. Caldwell, "Electric Utility Systems Application of Dispersed Storage and Generation" Presented at the IEEE PES Summer Meeting, Vancouver, British Columbia, Canada, July 15-20, 1979.
- (2) Frederick, W. A. et al., "A Fully Interconnected Wind System," Presented at Operational and Economic Status and Requirement of Large Scale Wind Systems Workshop, Monterey, Calif., March 1979.
- (3) Data Sheet on PP&L's Harwood Wind Electric Station.
- (4) Black, T. W., "PP&L Tests Power from the Wind," Power Engineering, July 1979.
- (5) Suelzle, L. R. and D. J. Roesler, "Operational Characteristics of a 60-kW Photovoltaic System Integrated with a Utility Grid," Presented at the 1979 Photovoltaic Solar Energy Conference, Berlin, West Germany, April 23-26, 1979.
- (6) Roesler, D. J., "A 60-kW Solar Cell Power System with Peak Power Tracking and Utility Interface," U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia.
- (7) Fact Sheet - United States Air Force - Mt. Laguna Air Force Station, California.
- (8) DOE News: "World's Largest Solar Cell Electric Power Station Activated," U.S. Department of Energy, August 15, 1979.
- (9) Data Sheet Mt. Laguna Air Force Station, California.
- (10) Stambler, I., "Cogeneration to Save Rohr \$90,000 a Year," Gas Turbine World, Nov. 1977.
- (11) Advice 440-E Public Utilities Commission of the State of California, File No. PUC 110, Proposal No. 877-E, Nov. 30, 1977.

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Abstract - In this paper many factors involved in the integration of Dispersed Storage and Generation (DSG) sources into electric utility distribution systems are presented. Both connection of DSG to the system and the operation of a DSG-equipped distribution system are discussed. A hierarchical control structure for system operation is proposed. A preliminary set of monitoring and control functions for system operation is developed.

INTRODUCTION

As the cost of conventional fuels has increased, and their availability has decreased, other means of generating electricity have attracted a great deal of attention, particularly those which do not use the scarce resources. Solar and wind based generation are examples. Many of these new sources are either too small or are located geographically such that it is not practical or economical to integrate them at the bulk generation level. They can more suitably be integrated at the distribution level.

The term Dispersed Storage and Generation (DSG) is defined as any source of electrical energy (including storage elements which act as sources at times) connected to a utility distribution system.

Before any form of DSG can be integrated into electric utility distribution system many economic and technical factors need to be considered. Among these are operational considerations. This paper discusses the integration of DSG units into the utility system in general, and the requirements for system operation, monitoring, and control in particular.

DSG TECHNOLOGIES

The principal alternate energy sources relevant to electric utility distribution systems are: a) solar thermal, b) photovoltaics, c) wind, d) fuel cells, e) cogeneration, and f) battery storage.

Solar Thermal

This technology is under development; some pilot plants are in the planning stage and some are under

construction. The range of solar thermal plant outputs is from 0.1 to 100 MWe or higher. Plants may use central receiver or distributed receiver concepts [1].

Photovoltaics

The photovoltaic process utilizes solid state devices to generate electricity directly from light. Direct current is produced and is subsequently converted to ac power. The power output range of these systems is from 1 kWe to 10 MWe or higher.

Wind

Many experimental wind powered generators are now in operation or are being planned [2]. Their power output ranges from 1 kWe to 10 MWe, depending on the number of and size of units comprising a "generation plant".

Fuel Cells

Fuel cells are devices which convert chemical energy directly into electrical power. Present programs are concentrating on the near term introduction of dispersed phosphoric acid fuel cell plants. These plants (5-10 MWe) will use light distillate fuels. The first demonstration plant to be operated in an actual utility environment will be a 4.5 MWe ac fuel cell module developed by United Technologies Corporation, which is to be installed in Consolidated Edison's system [3-6]. Incorporation of fuel cells rated at 26 MWe into electric utilities is also planned. From a technology point of view, fuel cells could be in commercial electric utility service by 1985.

Cogeneration

Cogeneration refers to the simultaneous generation of electricity and process heat. There are substantial cogeneration opportunities in petroleum refining, and in the cement, paper, and other industries. The power range is from a few kWe to 100 MWe or higher. Several electric utilities (e.g., San Diego Gas and Electric) are currently involved in cogeneration.

Battery Storage

The potential of lead acid batteries (and other types of batteries) for electric utility load leveling purposes is being investigated.

INTEGRATION OF DISPERSED STORAGE AND GENERATION

By the term integration we refer 1) to a connection to a utility system in which provisions are made for the protection of the DSG as well as the system, and 2) to the operation of the DSG as a managed part of the total utility supply system.

A single DSG unit of relatively small output - or a number of DSG units whose aggregate output is small - may be connected to a system without being "integrated". That is, they may be connected but not operated as a managed part of the supply mix. For purposes of this paper, such DSGs are defined as not fully integrated into the system, even though their output benefits the system. Thus, integrated operations require interaction, among the DSGs and the power system including the electric utility's bulk supply system.

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, Division of Electric Energy Systems under Interagency Agreement EC-77-A-31-1041 with the National Aeronautics and Space Administration and Contract No. NAS7-100.

A 79 494-6 A paper recommended and approved by the IEEE Transmission and Distribution Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Summer Meeting, Vancouver, British Columbia, Canada, July 15-20, 1979. Manuscript submitted February 5, 1979; made available for printing April 25, 1979.

Figure 1 shows the planning process for the development of a control system for integration of DSGs. In this paper, examples of applications of this process are shown, representing a "first iteration" as indicated on the Figure.

In this paper, emphasis is placed on the control system requirements imposed by integration of DSG. In determining the functions and the configuration of the control system required for integration of DSG we must consider both the requirements imposed on the system by DSG and the requirements the system imposes on the DSG. Tables I and II provide an overview of considerations from these two perspectives, leading to an understanding of general requirements. Considerations most clearly related to control system functions and design are underlined.

For an overall representation of an electric system with DSG, see Fig. 2.

GENERAL REQUIREMENTS

In this section, the "considerations" are reviewed and the specific considerations which most clearly relate to control system requirements are collated. (See Table III.) This is intended to serve as a general statement of the requirements to be met by the control system for integration of DSG.

Once the general requirements have been identified, the functions of the DSG control system for the integration of DSG plants into the utility system may be identified. These functions of the control system may be considered in a number of categories or groupings of general functions. Each function must ultimately be defined by detailed specific performance characteristics. For the purposes of this paper, the functions will be described but not defined by such performance characteristics.

MONITORING AND CONTROL FUNCTIONS REQUIRED FOR INTEGRATION OF DSG INTO UTILITY DIST. SYSTEMS

Various DSG technologies will be integrated into the distribution system at different points. These devices, on one hand, will produce added flexibility and new means for operating the distribution system, and on the other hand will necessitate the addition of new operational capabilities for DSG related operations. A control hierarchy must be defined and the monitoring and control functions for each level of the hierarchy will have to be investigated.

Control Hierarchy

As more and more DSG devices are integrated into the utility distribution system, additional capabilities are needed for the management, coordination and operation of the DSG facilities. This will require expansion of the existing supervisory control systems and will introduce further complexity into the design and operation of utility systems.

As discussed previously, it is likely that DSG devices will be integrated into electric utility distribution systems at various levels. Smaller sized units are likely to be integrated at the residential and small customer level, whereas medium sized units may be integrated at feeder or distribution substation level. Larger sized units are more likely to interface with subtransmission or be integrated at the bulk level. Since DSG elements will be located at sites throughout the distribution system, the DSG equipped distribution system will not be well suited to centralized control of operations. The massive data transfer and communication requirements suggest that a hierarchical structure for the supervisory control system will be more suitable. A hierarchical structure refers to a multi-level organization of monitoring and decision making in which each level is managed by the level below above.

A conceptual diagram for the monitoring and control system for a DSG-equipped distribution system is shown in Fig. 3. It is a five hierarchical level structured system. These levels are

1. Utility energy management.
2. Distribution system energy management.
3. Distribution substation energy management.
4. Feeder energy management.
5. Local/DSG facility energy management.

The five levels of hierarchy above may be implemented in a system which has less than five separate physical locations. For example, feeder energy management and distribution substation management systems may be located at the distribution substation.

There are also several levels of hierarchy above the utility energy management level (e.g., power pools and regional coordination center). Utility energy management involves the operation of the entire utility system. It is carried out from the utility energy management control center (EMCC). EMCC is in charge of the operation of central generation, transmission, and all

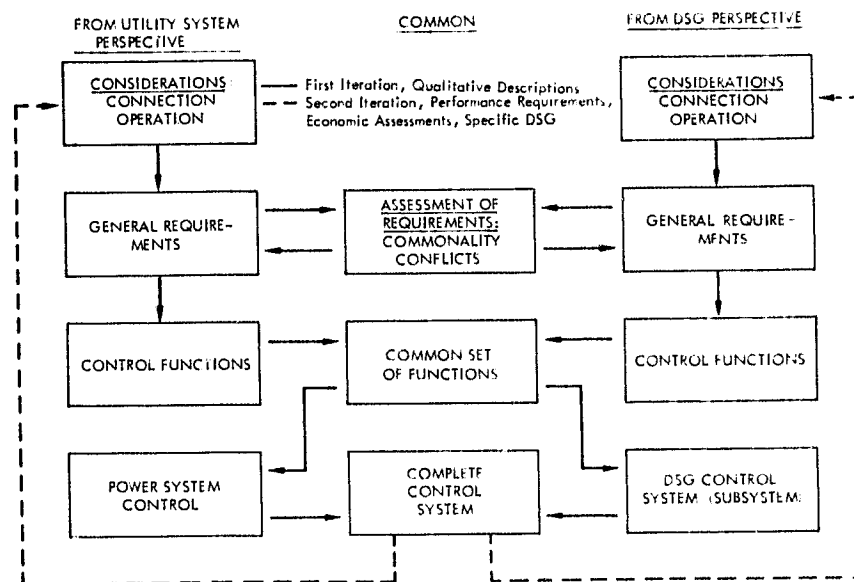


Fig. 1. Flow chart showing the planning process for the development of the control system for integration of DSGs.

Table I. DSG connection considerations.

From the Utility System Perspective	From the DSG Perspective
<p><u>Why</u> add DSG to the supply mix?</p> <ul style="list-style-type: none"> • Lead time for construction may be shorter than for alternatives • May offer siting flexibility • Circumstances related to availability of renewable resources may dictate dispersed locations • There may be opportunities for symbiotic relationships between the utility and a customer or groups of customers, e.g., <u>cogeneration</u>, other opportunities for beneficial use of waste heat, etc. <p><u>What</u> are the characteristics of the DSG?</p> <ul style="list-style-type: none"> • Initial costs: compared to alternatives • <u>Impact on system protection provisions</u> • <u>Impact on power system design and construction</u> • <u>Impact on provisions for safety of personnel and property, systemwide</u> <p><u>Where</u> will the DSG be installed? (See Fig. 2)</p> <ul style="list-style-type: none"> • <u>On customer premises; consider impacts on design and construction for locations at residences, other small to medium sized customers, major customers on dedicated feeders or on the subtransmission system</u> • <u>On utility facilities:</u> <ul style="list-style-type: none"> <u>Primary laterals</u> <u>Feeders</u> <u>Distribution substation</u> <u>Subtransmission system</u> • <u>On properties in the public domain or under control of quasi-governmental agencies, e.g., flood control channels, settling basins, etc.</u> • <u>Effect of location on the communication system</u> • <u>Effect of location on the utility control system</u> • <u>Effect of location on system capabilities, flexibility, reliability</u> <p><u>How</u> will connection of DSG to the System affect design and construction?</p> <ul style="list-style-type: none"> • <u>If DSG generates VARS, it may be incorporated as part of voltage regulation equipment. Affects locations of capacitors, regulators, etc.</u> • <u>Control system revisions and incorporation of DSG imposed requirements</u> • <u>Possible EMI, to or from DSG, design considerations</u> • <u>System stability-measures to mitigate negative effects on and by DSG</u> • <u>Safety considerations</u> <p><u>When</u> will different DSG be available for addition to the system?</p> <ul style="list-style-type: none"> • <u>Storage</u> • <u>Generation</u> • <u>Specific technologies</u> • <u>Cost, cost effectiveness</u> • <u>Sizes</u> • <u>Indication to DSG development programs of design requirements for system connection</u> 	<p><u>Why</u> connect DSG to the utility system?</p> <ul style="list-style-type: none"> • <u>Connection to system may reduce need for standby or start-up energy system</u> • <u>Integration with utility system control may reduce requirements for local control capabilities, hardware, software</u> • <u>Sizing of DSG maximum capability may be beneficially affected by availability of supplemental capacity from the system (not required to meet peak local need)</u> <p><u>What</u> are the characteristics of the utility system?</p> <ul style="list-style-type: none"> • <u>Effects of system requirements on initial DSG costs</u> • <u>Impact on DSG protection provisions</u> • <u>Impact on DSG power processing design and construction</u> • <u>Impact on safety of personnel and property at the DSG location</u> <p><u>Where</u> will control be exercised in the utility system? (See Fig. 3)</p> <ul style="list-style-type: none"> • <u>DSG position in the system control hierarchy.</u> • <u>Adequacy of the utility control system and the assurance that it will not cause malfunction or improper operation of the DSG</u> • <u>Communication related requirements</u> • <u>Interface between local DSG control and power system control</u> <p><u>How</u> will connection to the utility system affect DSG design construction?</p> <ul style="list-style-type: none"> • <u>Voltage regulation provisions</u> • <u>Protection system</u> • <u>Quality of generated sine wave harmonics</u> • <u>Stability considerations, excitation response times, planning and design considerations</u> • <u>Governor or equivalent need not provide load-following capability</u> • <u>Required Ratings (momentary, etc.) of equipment and conductors/busses may be increased due to higher fault capacity of system</u> • <u>Possible EMI, to or from utility system, design considerations</u> • <u>Safety considerations, for utility system personnel or equipment</u> <p><u>When</u> will the utility control system be capable of connecting to and controlling the DSG?</p> <ul style="list-style-type: none"> • <u>At each location, e.g., feeders, laterals, substations, etc.</u> • <u>Control system capability</u> • <u>Communications system capability</u> • <u>Indication to Utility Systems of design Requirements for DSG connection</u>

Table II. DSG operation considerations.

From the Utility System Perspective	From the DSG Perspective
<p><u>Why add DSG to supply mix?</u></p> <ul style="list-style-type: none"> • Fuels may be more abundant or consistently available • System losses may be reduced • <u>Flexibility during restorative state</u> • <u>Flexibility/reliability related to specific essential loads</u> <p><u>What are the characteristics of the DSG?</u></p> <ul style="list-style-type: none"> • Electrical characteristics: capacity, annual plant factor, capability • Availability factor • <u>Generating or storage DSG</u> • <u>Response times, load following capabilities</u> • <u>Characteristics under transient conditions</u> • <u>Pollutants, effluents, noise generated?</u> • <u>Potential hazards?</u> <p><u>Where will the DSG be installed?</u></p> <ul style="list-style-type: none"> • <u>Provisions for operation and maintenance, for customer site locations</u> • <u>Priority of customer use of DSG output for DSG on that customer's site</u> • Impact on operations and maintenance personnel and equipment, due to dispersed locations • Impact on response times for emergency maintenance, repairs, due to dispersed locations <p><u>How will DSG impact system operations?</u></p> <ul style="list-style-type: none"> • <u>May require special considerations as regards DSG "Capacity" assessment</u> • <u>May provide system energy storage</u> • <u>May offer flexibility in managing the total effluents for supply system</u> • <u>May assist or complicate efforts to maintain services to essential loads during disturbances</u> <p><u>When will different DSG be available for operations?</u></p> <ul style="list-style-type: none"> • Planning for operations and maintenance personnel • Data acquisition for planning for connection and operation of DSG • <u>Indication to DSG technology development programs of system operating requirements</u> 	<p><u>Why connect DSG to the utility system?</u></p> <ul style="list-style-type: none"> • Flexibility for maintenance • Annual plant factor may be increased, affecting cost/benefit analysis • <u>DSG may benefit from either 1) base load type operation or 2) access to load sink, allowing output to be matched to available (economical) input energy levels</u> <p><u>What are the characteristics of the utility system?</u></p> <ul style="list-style-type: none"> • Fault capacity • Capacity as energy source and sink • <u>Transient conditions characteristics</u> • <u>Quality of the sine wave</u> • <u>Generated harmonics</u> • Equivalent impedance, power transfer capabilities (looking from DSG location) • <u>Reliability, continuity of service at system location for DSG connection</u> <p><u>Where will control be exercised in the utility system?</u></p> <ul style="list-style-type: none"> • <u>Real time access to control system</u> • <u>Provisions for override, blockage of starts</u> • <u>DSG control under conditions of failure of the utility control system</u> • <u>Level of authority of the local DSG control</u> • <u>Status, telemetry, control responsibilities arising from connection to the utility system</u> <p><u>How will the system impact DSG operation?</u></p> <ul style="list-style-type: none"> • Maintenance cycles may be modified to accommodate system needs • <u>Operation in excess of normal ratings may be required, due to system needs</u> • <u>Loading levels may be dictated by total system needs, not just local needs</u> • Effects of system disturbance may affect DSG more than if in a "stand alone" mode • <u>Operation of DSG dictated by real time evaluation of total supply mix, economic dispatch, rather than in consideration of local needs and economics</u> <p><u>When will the utility control system be capable of controlling DSG?</u></p> <ul style="list-style-type: none"> • <u>Planning within DSG technology development for interface with utility systems</u> • <u>Indication to utility systems of pending DSG operating requirements</u>

distribution systems. Distribution system energy management is achieved at the distribution system control center (DSCC). DSCC receives commands from and sends information to EMCC. Additionally, DSCC manages all the levels below it, which include large customer DSG facilities and distribution substation control systems. Distribution substation energy management is achieved through the distribution substation control system (DSSCS). DSSCS receives control commands from and sends information to DSCC. It also manages the facilities that are connected to the distribution substation, which

include any DSG facilities directly connected to the distribution substation and the distribution substation feeders. Feeder energy management is achieved through the feeder control system (FCS). FCS receives control commands from and sends information to DSSCS. It manages all the DSG facilities connected to the feeder, and the local/DSG facilities energy management systems. Local/DSG facility energy management is achieved at the DSG facility control system.

Each DSG facility has a local control system associated with it. The purposes of this control system are

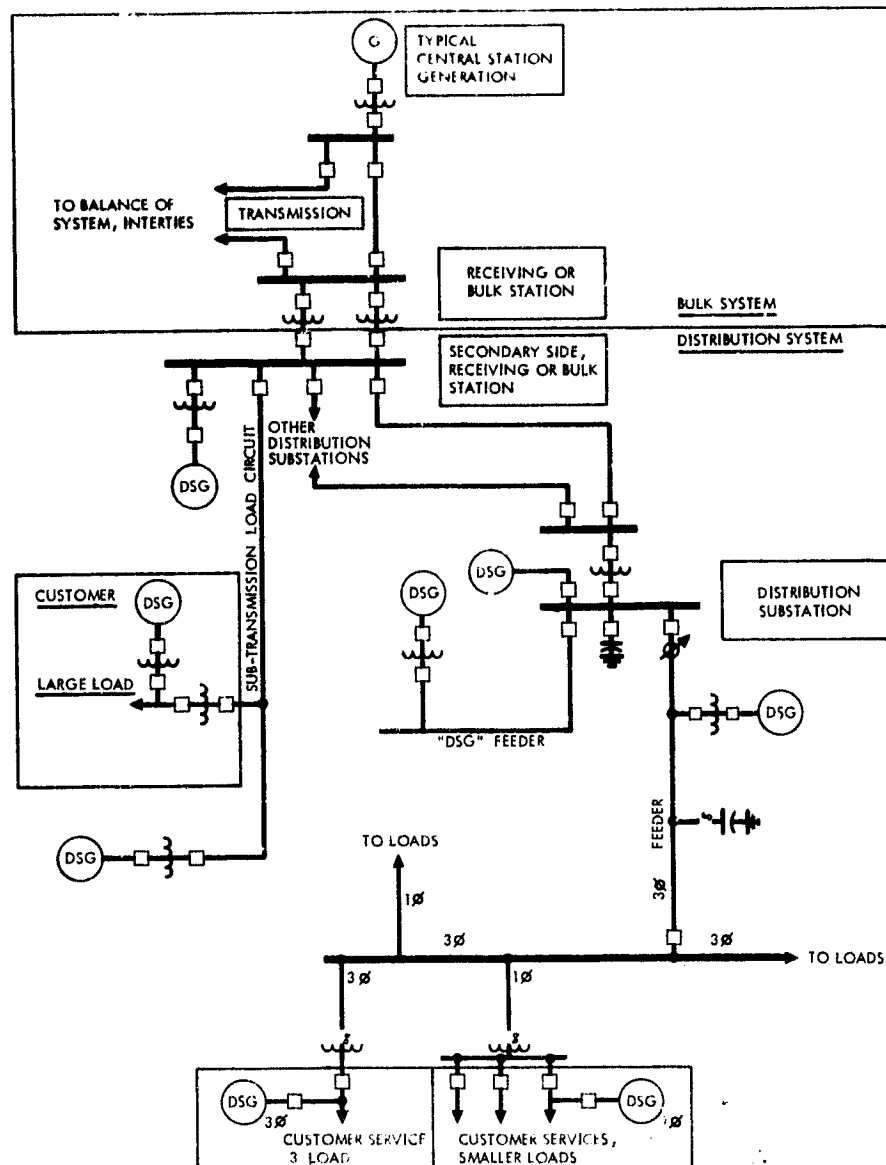


Fig. 2. Simplified electric system with DSG.

1. To send appropriate monitoring information to the appropriate higher level control center.
2. To receive operational commands from the appropriate higher level control center.
3. Operate the DSG unit.

In the case of residential and/or small customer DSG units, and medium sized DSG units, the DSG local control system interfaces with the feeder control system. The control system for DSG units located at distribution substation, and the control system for large customer DSG units, directly interface with, respectively, the distribution substation control system and the distribution system control system.

A great deal of activity will take place within each of the control systems. Furthermore, a great deal of information must be exchanged among appropriate systems. The latter requires the implementation of certain communication functions, which will not be discussed here. However, the functions required to carry out the activities in the control system as related to the operation of a DSG-equipped utility distribution system will be discussed in detail.

Monitoring and Control Functions

In order to implement the proposed hierarchical control system for the operation of a DSG-equipped distribution system, a set of monitoring and control functions needs to be developed and implemented. Here we will present a preliminary set of monitoring and control functions needed for the operation of DSG within a distribution system, as well as the operation of a DSG-equipped distribution system.

These monitoring and control functions may be categorized as follows:

1. Monitoring functions.
2. Processing and decision functions.
3. Control functions.
4. Recording functions.

Monitoring functions refers to the functions indicating various system states (state observation vector). These functions may be the acquisition of analog readings (indications) or digital status information.

Table III. General requirements for integration of DSG
(control system requirements)

From the Utility System Perspective	From the DSG Perspective
<p>Requirements which arise from consideration of the dominant characteristics of the DSG:</p> <ul style="list-style-type: none"> • Storage or generation • Storage, varying ratios of peaking capacity to nominal output • Generation, base operation capability • Generation, intermittent capability • Generation, load following capability • Generation, capacity "firm", partially "firm" or "non-firm" (energy source only). • Size (electrical output) <p>Requirements which arise due to system level and location (subtransmission, distribution substation, feeders, laterals, customer substations/services) of the DSG interface:</p> <ul style="list-style-type: none"> • Additions to control system • Power flows, voltage regulation • Assignment of DSG output to selected loads (during times of systems failures) <p>Requirements which arise from different conditions of operation.</p> <ul style="list-style-type: none"> • DSG operations during various utility system states: <ul style="list-style-type: none"> Normal Pending emergency (preventive) Outage Restorative • Voltage regulation, real and imaginary power outputs, frequency control, synchronizing; under each state <p>Requirements which arise from need to exchange information with the DSG.</p> <ul style="list-style-type: none"> • Metering and status information, as required for system operations and analyses. 	<p>Requirements which arise from consideration of the dominant characteristics of the utility system:</p> <ul style="list-style-type: none"> • Always a load sink? • Needs for DSG output vary? • Availability for backup, startup energy? <p>Requirements which arise due to system level and location of the utility system interface:</p> <ul style="list-style-type: none"> • Implications on control system security, hierarchy location. • Impacts on operations, perceived need for DSG output, availability of system capacity. <p>Requirements which arise from different conditions of operation.</p> <ul style="list-style-type: none"> • System operations during various DSG states: <ul style="list-style-type: none"> Normal Pending emergency (preventive) Outage Restorative • Voltage regulation, real and imaginary power outputs, frequency control, as affected by system needs under each state. • Location in control hierarchy under each state. • Control system role in personnel and equipment safety under each state. <p>Requirements which arise from need to exchange information with the utility system.</p> <ul style="list-style-type: none"> • Metering and status information as required for DSG operations and analyses.

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Examples of these are readings of various system voltages or acquiring the status of a given breaker. Processing and decision functions are those that act on the input data and commands, and determine what control functions are to be exercised. Examples of these are functions implementing control strategies, economic dispatch, and changes in real and/or imaginary power levels. Control functions refers to functions used to make the desired and possible changes in the system. Examples of these are voltage regulation (control), and DSG output power control. Finally, recording functions are those needed to document the desired information; for example, DSG output power (history).

Distribution System Control Center Functions

The distribution system control center manages the entire distribution system and coordinates the activities of the distribution substation control systems and

those of a large customer DSG local control systems. A preliminary list of major monitoring and control functions that may be implemented at this level is given in Table IV.

Distribution Substation Control System Functions

This control system is responsible for the overall operation of all the facilities within a distribution substation, as well as coordination and management of feeder control systems and distribution substation DSG local control systems. A preliminary version of the major functions to be implemented at the distribution substation control system is given in Table V.

Feeder Control System Functions

The feeder control system coordinates and manages all the DSG facilities connected to the feeder, as well as the residential and/or small customer DSG facilities.

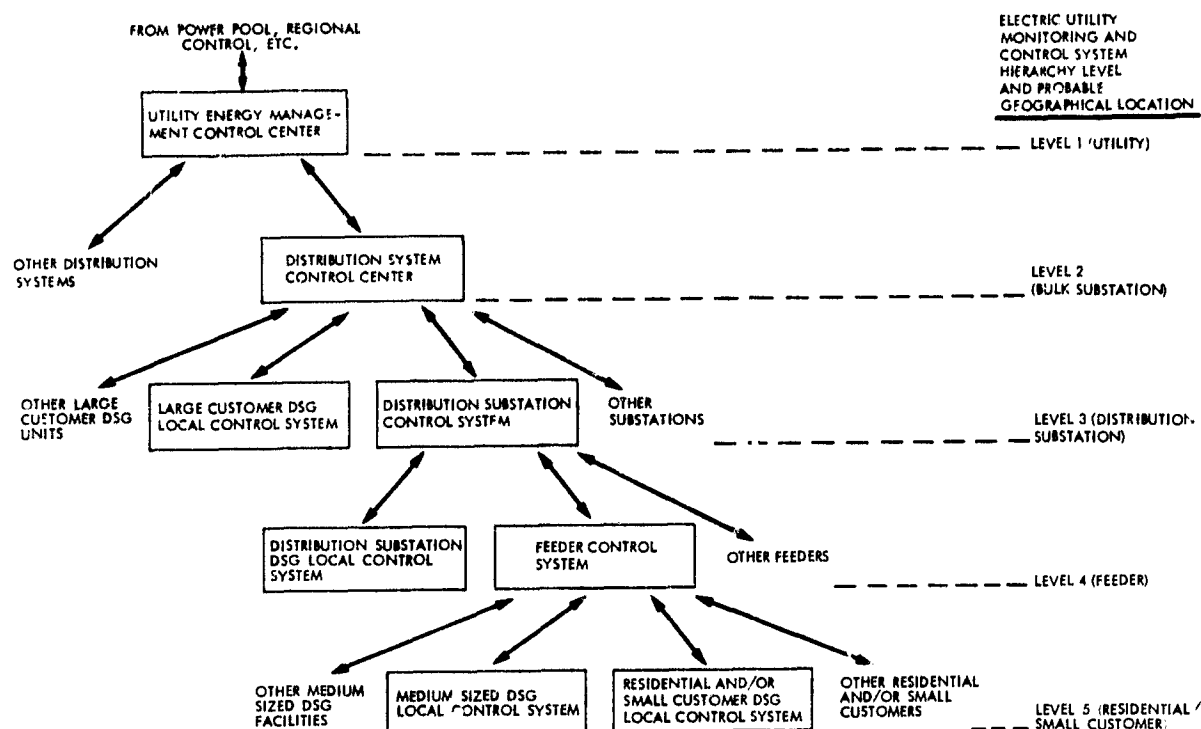


Fig. 3. A conceptual diagram for the monitoring and control system for a DSG-equipped distribution system.

A preliminary list of major monitoring and control functions to be implemented at the local DSG facility is given in Table VI.

Local DSG Functions

Associated with each DSG facility, there is a local control system. This system is responsible for operating the DSG facility under the general management of a higher level of control hierarchy. A preliminary list of major monitoring and control functions to be implemented at the local DSG facility is given in Table VII.

CONCLUSIONS

Recently, generation of electrical power from alternate resources has attracted a great deal of attention. Power plants based on solar thermal, photovoltaics, wind, or waste energy are being considered for integration into electric utility systems. Batteries are being considered as a means of providing a mechanism for load leveling for the system.

Many of these new electric power sources will be integrated into the electric utility distribution system, and are thus termed Dispersed Storage and Generation (DSG) sources.

Table IV. Distribution system energy management monitoring and control functions (preliminary).

Monitoring Functions	Processing and Decision Functions	Control Functions	Recording Functions
<ul style="list-style-type: none"> • Fault identification • Monitoring of abnormal conditions • Monitoring of clearances, other constraints on actions • MW, MVAR flow monitoring • Receive information from distribution substation control systems • Receive information from large customer DSG local control systems • Receive operational commands from EMCC • Synchro-check • System load monitoring • Transformer load monitoring 	<ul style="list-style-type: none"> • Component loading • Control and operational strategies • Data processing for studies • Diagnostic check • Economic Dispatch • Fault identification • Load management • State estimation • System display generation 	<ul style="list-style-type: none"> • Capacitor control • Fault clearing, isolating and restoring service • Issue commands to distribution substation control system • Load control • MW, MVAR flow control • Send commands to large customer DSG local control systems • Transformer load control • Underfrequency load shedding • Voltage control 	<ul style="list-style-type: none"> • Data recording for studies • Fault documentation, sequence of events magnitude, effects

Table V. Distribution substation energy management monitoring and control functions (preliminary).

Monitoring Functions	Processing and Decision Functions	Control Functions	Recording Functions
<ul style="list-style-type: none"> Equipment monitoring Feeder load monitoring Monitoring of clearances, other constraints on actions MW, MVAR flow monitoring Receive information from feeder control system Receive information from distribution substation DSG local control system Receive operational commands from distribution system control system Synchro-check Transformer load monitoring 	<ul style="list-style-type: none"> Component loadings Control and operational strategies Data processing for studies Diagnostic checks Economic dispatch Fault identification Load management State estimation 	<ul style="list-style-type: none"> Capacitor control Fault clearing, isolating and restoring service Issue commands to distribution substation DSG local control systems Issue commands to feeder control systems Load control MW, MVAR flow control Power management among feeders Transformer control Underfrequency load shedding Voltage control 	<ul style="list-style-type: none"> Data recording for studies Fault documentation Feeder powers Feeder voltages Metering

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Table VI. Feeder energy management monitoring and control functions (preliminary).

Monitoring Functions	Processing and Decision Functions	Control Functions	Recording Functions
<ul style="list-style-type: none"> Equipment monitoring Feeder load monitoring Monitoring of clearances, other constraints on action MW, MVAR flow Receive information from medium sized DSG local control systems Receive operational commands from distribution substation control system Receive information from residential and/or small customer DSG local control systems Synchro-check Transformer load monitoring 	<ul style="list-style-type: none"> Component loadings Control and operational strategies Diagnostic checks Economic dispatch Fault identification Load management State estimation 	<ul style="list-style-type: none"> Automatic feeder reclosing Capacitor control Fault clearing, isolating and restoring service Feeder load control Issue commands to medium sized DSG local control systems Issue commands to residential and/or small customer DSG local control systems MW, MVAR flow control Transformer control Underfrequency load shedding Voltage control 	<ul style="list-style-type: none"> Data recording for studies Fault documentation Lateral powers Lateral voltages

Table VII. Local/DSG facility energy management monitoring and control functions (preliminary)

Monitoring Functions	Processing and Decision Functions	Control Functions	Recording Functions
<ul style="list-style-type: none"> DSG available capacity DSG breaker status DSG current output DSG delta frequency DSG failure DSG fuel supply DSG loading DSG phase angle DSG reactive power DSG real power DSG temperature DSG voltage Equipment monitoring Monitoring of clearances, other constraints on action MW, MVAR flow Receive operational commands from feeder control system Synchro-check 	<ul style="list-style-type: none"> Component loadings Control and operational strategies Data processing for studies Developing DSG state information Diagnostic check Fault identification Load management 	<ul style="list-style-type: none"> Connect/disconnect Fault clearing, isolating Load control Phase angle control Protection Reactive power control Real power control Shut-down Starting Underfrequency load shedding Voltage control 	<ul style="list-style-type: none"> Data recording for studies DSG energy DSG reactive power DSG real power DSG voltage On/off-line history

In this paper some of the general considerations for the integration of DSG sources into an electric utility distribution system were discussed. Factors that may affect the connection of DSG to the system and/or the operation of DSG within the system were presented. With respect to the operation of DSG within the system, a hierarchical control system was proposed, and a preliminary set of monitoring and control functions was developed.

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For the past three years, Dr. Bahrami has been a part-time faculty member of California State University at Los Angeles, where he has been teaching control and system theory courses. Since 1976 he has been an active reviewer of IEEE Transactions on Automatic Control.

A FULLY INTERCONNECTED WIND SYSTEM

MARCH 1979

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Presented at:

Operational and Economic Status and
Requirements of Large Scale Wind Systems
Workshop sponsored by U.S. Department of
Energy--Wind Systems Branch

Doubletree Inn
Monterey, California

A FULLY INTERCONNECTED WIND SYSTEM

INTRODUCTION

In November of 1977 the Pennsylvania Power & Light Company decided to install a wind turbine generator (WTG) that had a full three phase connection to the electrical distribution system. The objectives of the project were fourfold: (1) To get operating experience, (2) To determine a capacity factor in a favorable location, (3) To assure the safety of such an interconnection under all conditions, and (4) To study any disturbances and other effects that could cause difficulties with other customers.

Energy Development Company was in the process of installing two machines just west of Allentown (Dorney Park). Their ready availability and simple design made them a natural supplier for the PP&L project. The two Dorney Park windmills were 225 and 45 kw, respectively, but the line interconnections were only single phase 20 kw and 8 kw, respectively. The machine chosen for installation was EDC's Model 445, a 45 kw, four bladed machine with 45-foot diameter rotor and 40-foot tower. (See Figure 1.) The generator was three phase a.c. The unit has a brake that can be operated manually or automatically, in the latter mode it will shut the machine down at 35 mph. The unit is designed to survive gusts of up to 120 mph. The installation was supervised by T. Mehrkam, Energy Development Company, 179E RD #2, Hamburg, Pennsylvania 19526.

SITE DESCRIPTION

Three miles west of Hazleton, Pennsylvania, at a former generating station location, stands PP&L's first totally owned wind energy system. The site is approximately 1800 feet above sea level on a plateau atop a mountain range. Initially 40,000 square feet of area was cleared to minimize the effect of most natural wind obstructions. (See Figure 2.)

The research site is 100 feet x 125 feet, secured with Company standard fencing. Limited access is available via a construction grade road which has a locked gate at the PP&L property line. The area inside the fence

is stoned, while the perimeter area is seeded to facilitate maintenance over the life of the project. A 4/0 copper ground grid was buried just outside the fence. A ground grid extends to the base of the wind turbine tower at two points, 180° apart and to the control cubicle.

The control cubicle, a 12 foot x 20 foot prefabricated building, houses the power conversion equipment including controls and instrumentation. It is located at the southeast corner of the facility since predominant winds are West-Northeast-North.

The WTG is located 25 feet to the north of the center of the fenced area. Underground rigid steel conduits were installed for power and control from the base of the tower to the control cubicle.

An underground get-away ties the output of the station to three single phase, 25 kva, 7200/240 v standard pole mounted transformers just outside of the control cubicle. Using one overhead span the final interfacing connection is made to the Harwood #6 12 kv line.

MAJOR EQUIPMENT

The WTG, as purchased from Energy Development Corporation, consists of an 8 foot x 8 foot x 7 foot base collar, a 40 foot tower, a 45 foot diameter rotor, gearbox, a 45 kw 3-phase alternator, a control panel and 3-phase rectifier. This maximum rating, 45 kw, is considered a continuous rating in this application since maximum cooling will be in effect. The maximum rating is based on a 27 mph wind.

It is a down wind machine using a fixed blade pitch tuned for the individual geographical location. Speed control is accomplished through the load. A 3-phase generator was chosen since various inherent efficiencies of 3-phase systems are better. Larger machines would necessarily be 3-phase.

Since the generator produces a variable a.c. voltage and frequency due to changing wind conditions, it was decided not to connect it directly to the utility grid. We may try the direct connection as one of our future tests. The a.c. output from the generator is rectified to d.c. and fed to a synchronous inverter. A 500 ampere-hour battery is connected to the d.c. bus for energy storage and to provide a steady load to help regulate the d.c.

voltage and speed of the WTG. The voltage level of the battery system was chosen to optimize power transfer and matched for expected wind conditions such that the expected output of the WTG was as near as practical to the optimal battery float charge. (See Figure 3 - One Line Diagram.)

The wind turbine requires a yaw motor and a gear box to rotate the four fixed pitched blades down wind. The blades are designed to rotate free up to a 35 mph wind. At that time, an electrical brake will engage and then the mechanical brake. One of these brakes is mounted on the rotating blade shaft and the other mounted on the alternator shaft. A gear box connecting the two shafts steps up the alternator speed to blade speed by a ratio of 50 to 1.

The line commutated synchronous inverter (GEMINI S.I.) is rated at 50 kw, 3-phase, 240 vac output with a variable d.c. voltage input. The input voltage is limited by the peak a.c. output voltage for commutation. The synchronous inverter was designed and built by Gemini Company of Cedarburg, Wisconsin. Through control circuitry it maintains synchronism to the utility grid and fires pulses of power each half cycle into the established 60 Hz utility sine-wave form.

GEMINI S.I. DESCRIPTION

Its output is connected to the utility 12 kv distribution line through 3 - 25 kva, single phase, 7200/240 v standard pole mounted transformers. The connection is a wye to delta configuration.

The line commutated inversion process takes advantage of the fact that the a.c. line voltage swings periodically from zero to a positive peak, back through zero to a negative peak, and then to zero again. Thus, during each cycle there exists a time when this varying voltage is instantaneously equal to any arbitrarily selected value between zero and the peak magnitude.

If a source of d.c. voltage is connected to an a.c. line, electrical current will flow from the d.c. source to the lines whenever the d.c. voltage is greater in magnitude than the instantaneous a.c. voltage, and electrical current will flow from the a.c. lines to the d.c. source during the remainder of each cycle when the a.c. voltage is instantaneously larger than the d.c. source. Power is transferred back and forth periodically with the flow of these currents, but no useful net power flows in either

direction, currents being dependent largely upon source and line impedances, and no actual conversion of d.c. to a.c. exists.

If, however, a high speed switch is included in the circuit which connects the d.c. source to the a.c. lines, the connection can be made during the times when current will flow from the d.c. source to the a.c. lines, and broken during the times when reverse current would flow from the a.c. lines to the d.c. source. Power flow will therefor exist in one direction only, and a net amount of energy is transferred from the d.c. source to the a.c. lines.

In order for the resulting power transfer to be truly a.c., operation of the switch must include power transfers during both the positive and negative half cycles of the a.c. line voltage. This is accomplished by the use of a reversing type of switch for changing the relative polarities of the a.c. voltage as seen by the d.c. source, so that each half cycle will appear with the same polarity to the d.c. source, while actually reversing polarities at the a.c. line side of the switch.

Because of the nature of the switching action, power is transferred from the d.c. source to the a.c. lines in short pulses of power each half cycle. During the remainder of the half cycle, when no power is flowing from the d.c. source, the a.c. lines provide power to the connected loads. The relatively low line impedance as compared to the d.c. source forces the voltage to be essentially equal to line voltage at all times, and the switching action is synchronized to the a.c. line, so there is no tendency to upset the frequency.

If the a.c. line source voltage is interrupted, the GEMINI S.I. does not see an a.c. synchronizing pulse and, therefore, will not switch onto the line. This provides a built in safety feature, preventing the line from being energized solely by the WTG.

METERING

Metering of electrical parameters is accomplished by utilizing standard PP&L metering equipment. Also, these electrical quantities are recorded on magnetic tape recorder. Metering includes:

- A watt-hour meter at the output of the WTG.
- A watt-hour meter at the d.c. input to the line commutated inverter.
- A watt-hour meter at the a.c. output of the inverter, and
- A var-hour meter to measure the reactive power taken by the inverter.

Wind speed and wind direction are also recorded on the magnetic tape recorder. This information will be recorded on a time of day basis together with all power metering information. The information will be processed monthly for evaluation of the performance of the wind electric system.

BUILDING SERVICES

Building services includes HVAC, lighting and adequate power capacity for planned and possible future instrumentation, control and monitoring systems. All control building and other station loads are supplied from a separate single phase 120/240 volt a.c. service. A watt-hour meter has been provided for this separate station service power supply.

OTHER ITEMS

In addition to establishing a ground grid, lightning arresters were specified on the power cables at the control cable. Standard lightning arresters were used at the distribution transformers. Safety of personnel was accounted for throughout the design, operation and maintenance of the systems installed. Environmental impact was identified as minimal but esthetics were considered in the design.

OPERATION OF THE WIND TURBINE GENERATOR (WTG)

The PP&L WTG has been under initial trial operation and testing since October, 1978. Work associated with this initial operation has included: required "fine tuning" of the WTG by Energy Development Corporation (the manufacturer), complete inspection of all power conversion equipment including the line commutated inverter, and verification of proper connection of all metering and monitoring equipment.

The manufacturer of the WTG required 100 hours of manned WTG trial operation prior to PP&L operating the unit unattended. For this reason, PP&L personnel have operated the unit only when attended, and have been able to log nearly 100 hours of WTG trial operation as of February 28, 1979. The WTG and associated equipment to interconnect it to the PP&L system has performed quite satisfactorily to date.

Operating information collected to date indicates that the average wind velocity during this initial operating period has been in the range of 8 to 12 mph. Also, the corresponding average power output to the PP&L distribution system has been in the range of 3 to 6 kw.

This initial data is consistent with design curves which show typical behavior for a WTG such as the one being tested by PP&L. (See Figure 4, attached.) The curve shows no power output under 6 mph, then a gradual rise that is limited by the generator and power conversion equipment. The "cut-in" wind speed at which the unit can be synchronized (through the inverter) to the PP&L system is approximately 7 - 8 mph. However, when the unit is operating, the drop out speed is about four mph. The power output of the unit increases as indicated in the curve of the wind velocity until a maximum power output of 45 kw is reached at a wind velocity of 27 mph. The WTG will automatically shut down in wind speeds exceeding 35 mph by operation of a fail-safe braking system.

After the initial trial operation, the unit will be operated unattended except for periodic inspections, data collection and testing. An automatic yaw system will periodically position the WTG in the downwind direction. It will then begin operation automatically whenever the wind velocity reaches approximately 6 - 8 mph. The 'fail-safe' braking system that is used to stop the WTG in wind speeds exceeding 35 mph employs both a mechanical brake and an electrical brake (with backup battery power) with sufficient energy to maintain a stopped position of the turbine during hurricane force winds. In addition to the high windspeed shutdown feature, there are several other trouble conditions which will initiate automatic shut down for safety. They include: high vibration, overvoltage, control circuit malfunction, loss of WTG control power, and sustained loss of a.c. syn-

chronizing potential from the 12 kv distribution line. During unattended operation, the magnetic tape recorder located at the site will monitor and record, on a daily time of day basis, the performance data associated with station operation.

Also, radio trouble alarm indications received in the Local System Operators office in Hazleton, PA, will be used to monitor operating and trouble conditions at the station. A local alarm panel, located at the station, will help PP&L repair crew personnel identify problems.

During unattended operation, local PP&L personnel will inspect the station on a regularly scheduled basis to insure that: the station remains properly secured, all equipment is operating properly, and to perform periodic scheduled maintenance.

PLANS FOR WTG TESTING AND ENGINEERING ANALYSIS

The WTG will be operated unattended for a period of at least two years. During this time PP&L personnel will coordinate and conduct various tests. All of the testing, data collection and subsequent engineering analysis will be performed with the intent of completing the major objectives of the project as outlined in the Introduction of this paper.

Some of the more significant tests planned are as follows:

1. Under varying load conditions on the WTG (no load to full load) and using both an oscilloscope and oscillograph to monitor and record data, determine voltage and current magnitudes and accompanying wave-shapes at: (a) output of the WTG, (b) d.c. input to the inverter, and (c) 3-phase output of the inverter.

2. Under varying load conditions on the WTG (no load to full load), monitor and recorder instantaneous values of voltage, current, kw, kva at the:

- a. Output of the WTG.
- b. D.c. input to the inverter.
- c. Inverter a.c. output.

3. Under varying load conditions on the WTG (no load to full load), determine the corresponding values of wind velocity and wind turbine rotor speed.

4. At various power input levels to the synchronous inverter determine the corresponding output power and overall efficiency of the inverter.

5. At various power input levels to the synchronous inverter, determine the corresponding kw output and kvar input of the inverter, and the associated operating power factor.

6. Investigate and test for any TV, radio, or telephone interference due to WTG and/or inverter operation. This would include possible TV interference by reflection of the TV signal by the rotating blades.

7. Determine the magnitude and extent of harmonics superimposed on the PP&L distribution line due to inverter operation.

8. If possible, initiate a 'reclosure operation' on the PP&L 12 kv 3-phase line to determine the effect on the WTG when synchronized to this line.

9. Investigate the effect the WTG operation may have on other loads connected to the same 12 kv PP&L distribution line.

10. If possible, determine the effect of two inverters operating in parallel and synchronized to the same 12 kv, 3-phase PP&L distribution line.

11. Investigate the possibility of synchronizing the WTG directly to the PP&L 12 kv distribution line.

12. Investigate the concept of 'energy storage' through use of the storage battery to supply energy to the PP&L system during periods of light wind conditions, and allowing the WTG to supply energy to the PP&L system plus recharge the battery when wind conditions permit.

Using the data collected and recorded by the magnetic tape recorders and the data collected from various tests as outlined above, PP&L is determining the following:

1. The input power to the WTG and the corresponding output power.
From this, determine the power conversion efficiency of the WTG.
2. The power conversion efficiency of the rectifier.
3. The power conversion efficiency of the synchronous inverter.
4. The overall power conversion efficiency of the total system.
5. The reactive power taken by the inverter at various loads.
6. The average wind velocity at the Harwood site.
7. The average power in kw generated by the WTG at the average wind velocity for the site.
8. The total kw-hours that the WTG can be expected to generate on a monthly and yearly basis.
9. The availability and load factors associated with the WTG.
10. The total kvar hours that the PP&L system can be expected to supply to the WTG on a monthly and yearly basis.
11. The evaluated costs per kw hour for energy generated by the WTG over the projected life and how these costs compare to fossil fuel costs.
12. The compatibility of the WTG as interconnected to the PP&L distribution system.
13. The reliability and safety aspects associated with the interconnected WTG.
14. Also, additional analysis which will help to identify WTG performance will include establishing curves for (a) wind velocity vs. kw output for the WTG, (b) wind turbine speed vs. wind velocity, (c) inverter efficiency at various loads, and (d) inverter operating power factor at various input power levels.
15. Establish "PP&L Requirements and Guidelines" for PP&L customers who request to interconnect their privately-owned WTGs with the PP&L electric system.

PENNSYLVANIA POWER & LIGHT COMPANY
HARWOOD - 45 KW
WIND TURBINE GENERATOR

ENERGY DEVELOPMENT CO.
WINDMILL

1. TOTAL HEIGHT - 64 FEET
2. ROTOR - 45'-0" DIAMETER
3. BLADES - 20" WIDE
4. TOWER - 40'-0" HIGH
3'-0" DIAMETER
3/16" STEEL PLATE
5. STEEL COLLAR - 4'-0" HIGH
1/4" STEEL PLATE
6. ALLOWABLE SOIL BEARING
CAPACITY - 3000 P.S.F.

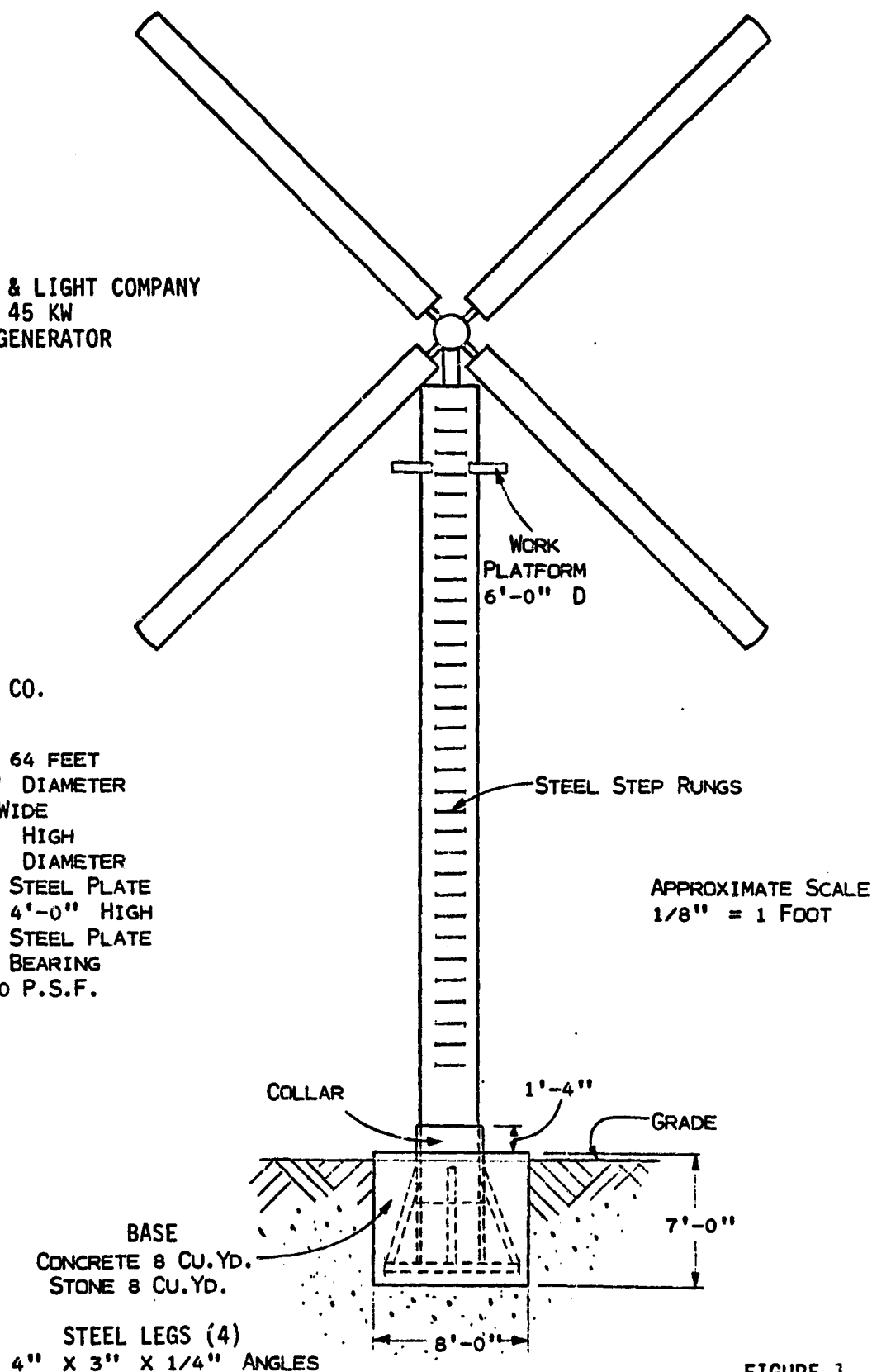


FIGURE 1

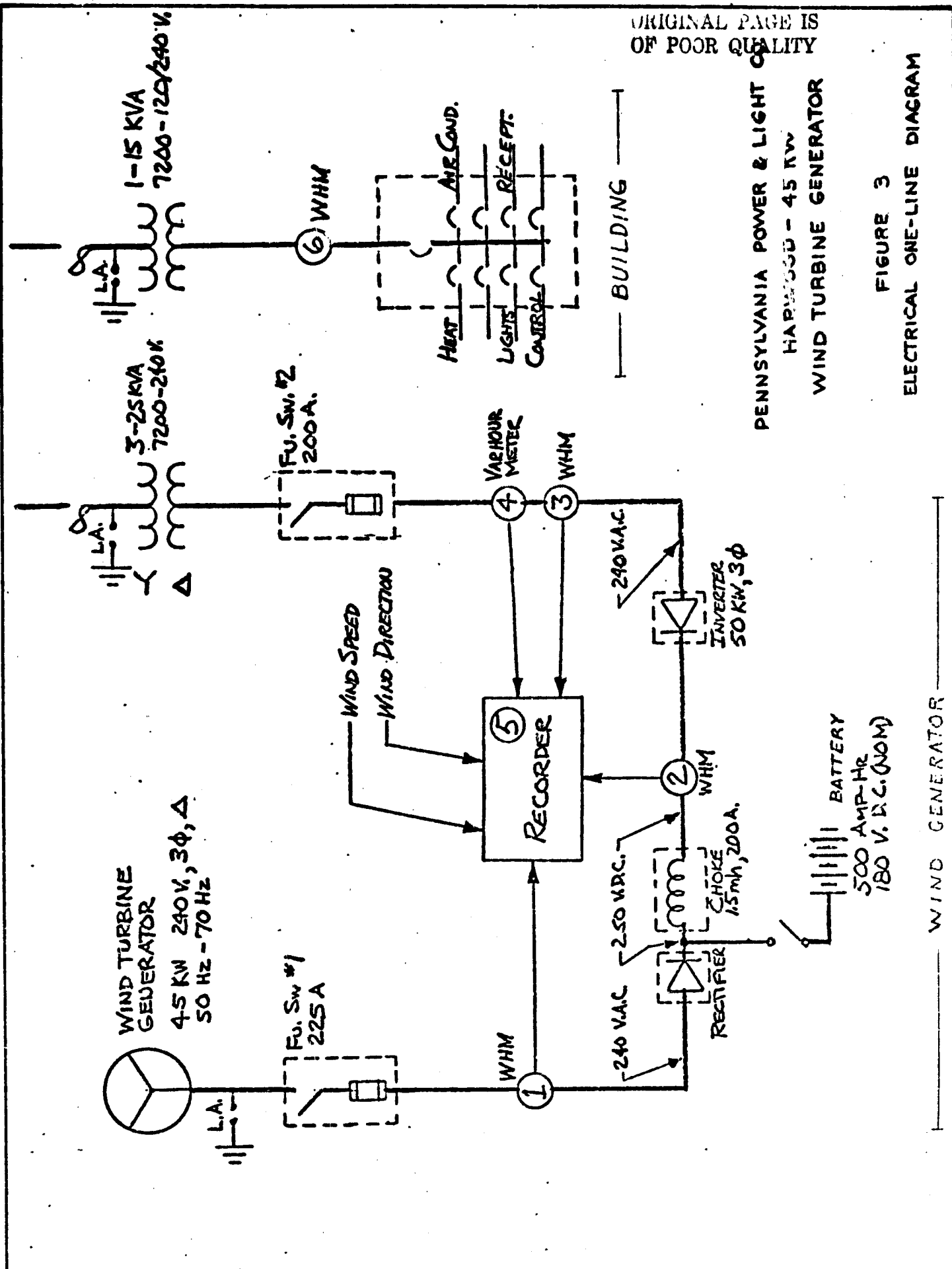
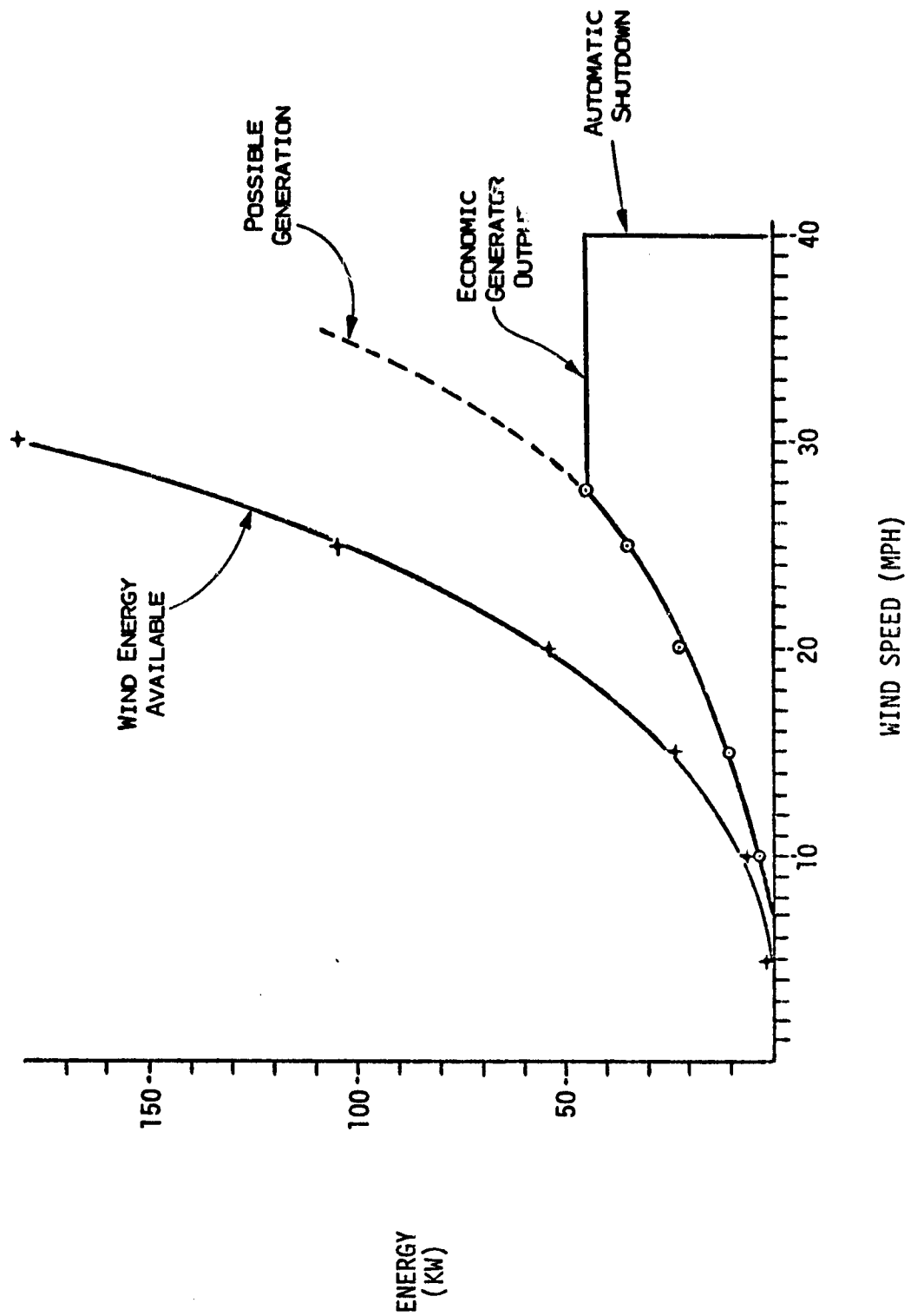


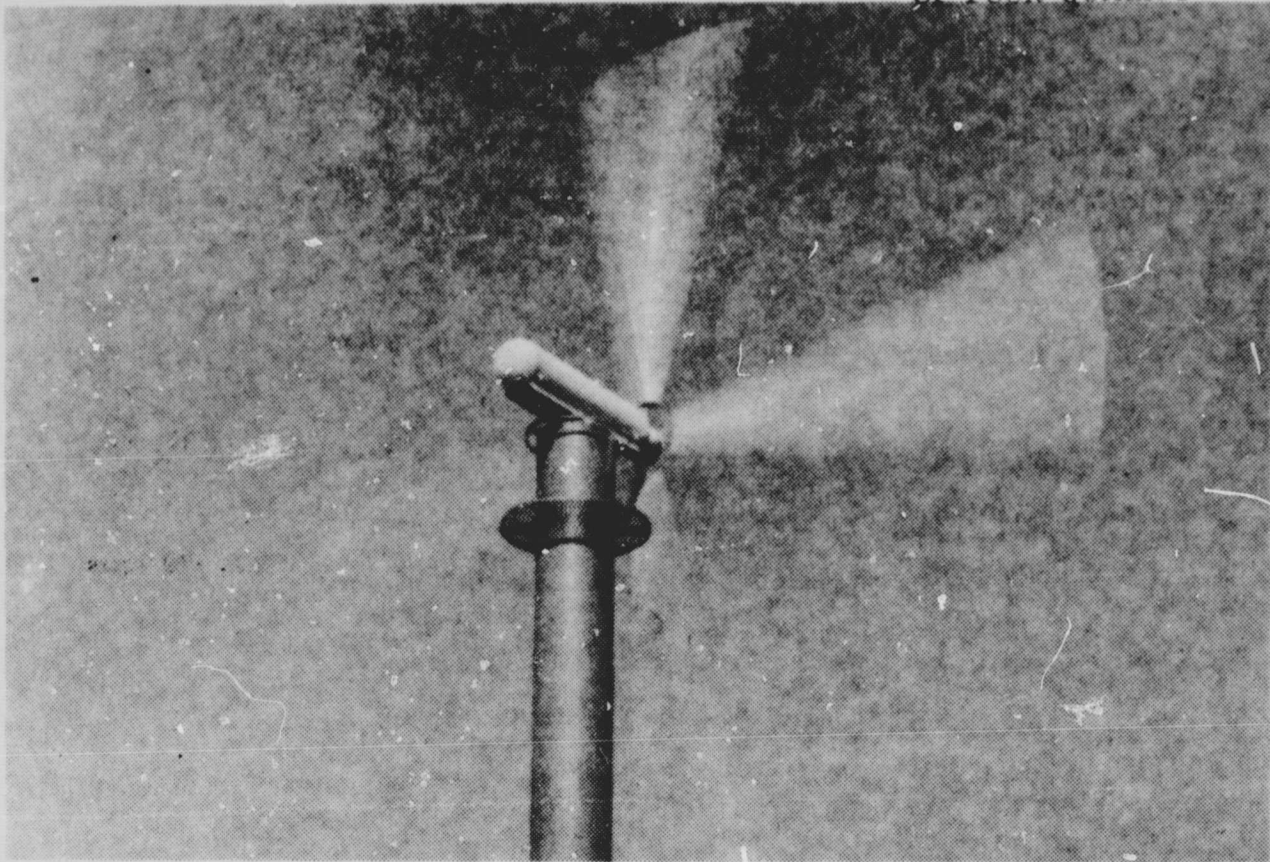
FIGURE 3

PENNSYLVANIA POWER & LIGHT COMPANY
HARWOOD - 45 KW
WIND TURBINE GENERATOR

FIGURE 4
WIND SPEED VS. ENERGY



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PP&L'S HARWOOD WIND ELECTRIC STATION

PURPOSE:

Harwood is an experimental station, intended to produce more information than electricity. Through its operation and continuing tests, PP&L hopes to:

- Compile data on reliability and performance of a small wind turbine
- Evaluate the effects of wind turbine operation on radio and television reception in the vicinity
- Learn how much use can be made of wind energy in the Harwood area
- Determine such a generator's compatibility with the PP&L system
- Formulate requirements for customer hookup of wind turbines to the PP&L system

LOCATION:

Near Humboldt Industrial Park in Hazle Township about three miles west of Hazleton

CAPACITY:

45 kilowatts maximum at 28 mph windspeed

OVERALL HEIGHT:

64 feet

TOWER HEIGHT:

40 feet

TURBINE:

Downwind design, with four 22-foot aluminum alloy blades

ALTERNATOR:

Statically excited, 1,800 rpm, three-phase, 240 volts A.C., maximum
45 kilowatts

RECTIFIER:

Input 100 amperes at 240 volts A.C. Output 100 amperes at 339 volts
D.C.

INVERTER:

50 kilowatts at maximum 250 volts D.C.

TRANSFORMERS:

Three 25 KVA single-phase units

REQUIRED WIND SPEED:

7-8 mph for startup, about 5 mph to maintain operation

INITIAL STARTUP & TESTING:

July 17, 1978

IN-SERVICE DATE:

September 22, 1978

OPERATION:

Seasonal, depending on prevailing winds

COST:

Tower, turbine-generator, related equipment	About \$25,000
Overall project	About \$190,000

ENVIRONMENTAL IMPACT:

The environmental impact of Harwood W.E.S. is expected to be minimal. It is located in a wooded area apart from major traffic routes, and color of the fencing and tower are designed to blend with the natural background.

9/78

PP&L tests power from the wind

Pennsylvania P & L is feeding synchronized power from a 45-kW rated wind turbine-generator into its distribution system. The two-year test is providing an insight into behavior of such units interconnected to a system

By THEODORE W. BLACK, Shimer-vonCantz, Inc.

Researchers at Pennsylvania Power & Light are testing the performance of a small wind turbine-generator (WTG) as part of a continuing PP&L-financed program in which different forms of energy technology are being assessed. Every aspect of the wind turbine generator's performance is being monitored as it feeds synchronized power into PP&L's distribution system.

The goal of the two-year wind energy research project is to identify the operating characteristics, safety aspects and any potential problems of the wind turbine-generator when it is interconnected to the PP&L system; establish requirements and guidelines for customers who wish to interconnect their privately owned wind turbine-generators with the PP&L distribution system; determine the reliability of the WTG system; examine the efficiency of the WTG system; examine the efficiency of the WTG in converting wind energy to electrical energy; determine actual power output that can be expected month by month

through several years; and determine the cost of power from the wind and how this cost compares with that of power generated by other means.

One of the ground rules for the tests is that the WTG must prove itself on its own. It would not be economical to have an operator constantly on duty at every unit, so PP&L's WTG has operated unattended since the completion of 100 hours of manned startup trials in May 1979.

The wind energy research station consists of the wind turbine-generator, Figure 1, and a 10 ft x 20 ft building that houses control panels, synchronizing equipment, performance monitoring and recording instruments, and a battery that stores power when it is not being supplied directly to the distribution system, Figure 2.

The station is within a few minutes' driving distance of the company's Harwood Substation near Hazleton, Pa. If there is a problem with the WTG or its associated equipment radio alarm indications are flashed to the

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local system operator in Hazleton, who dispatches personnel to correct the problem.

Typical of actual conditions in PP&L's service area, average wind velocity at the wind energy research station is 10 mph or less—rather low for efficient generation of power.

Standard wind energy hardware

PP&L's wind turbine-generator, designed and built by Energy Development Corp., Hamburg, Pa., is a standard, state-of-the-art machine, incorporating proved hardware. Rated output of the system is 45 kW maximum, 25 kW continuous duty, at a wind velocity of 27 mph. At that wind velocity, the WTG produces 240-V, 60-Hz, three-phase power.

Although the rated output is small by utility standards, PP&L researchers feel that most test results will be as valid for their WTG as they would be for a larger machine. Further, several virtually identical privately owned units are already in operation in this

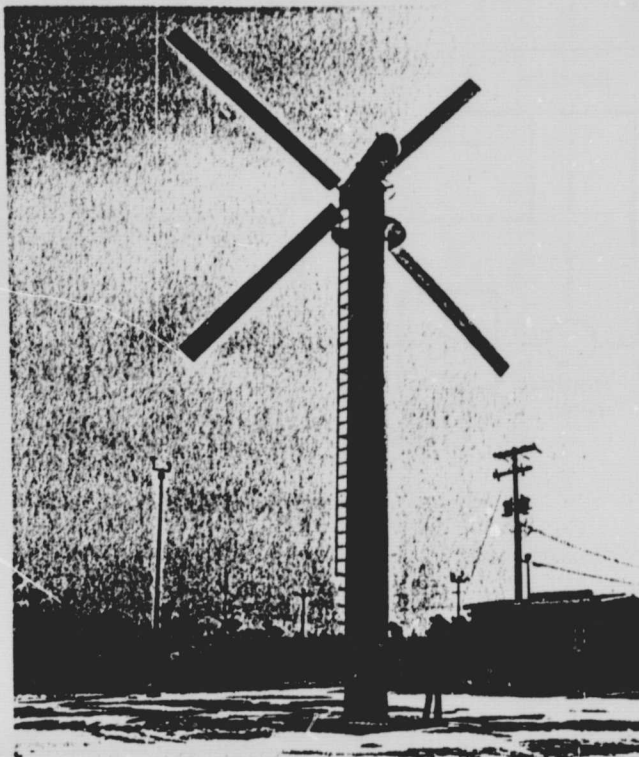
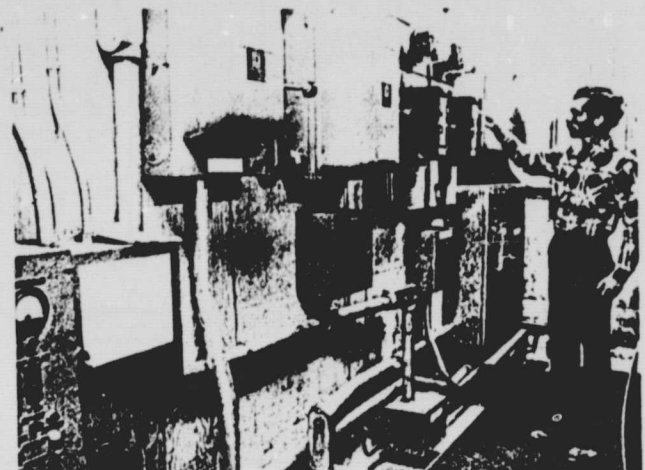


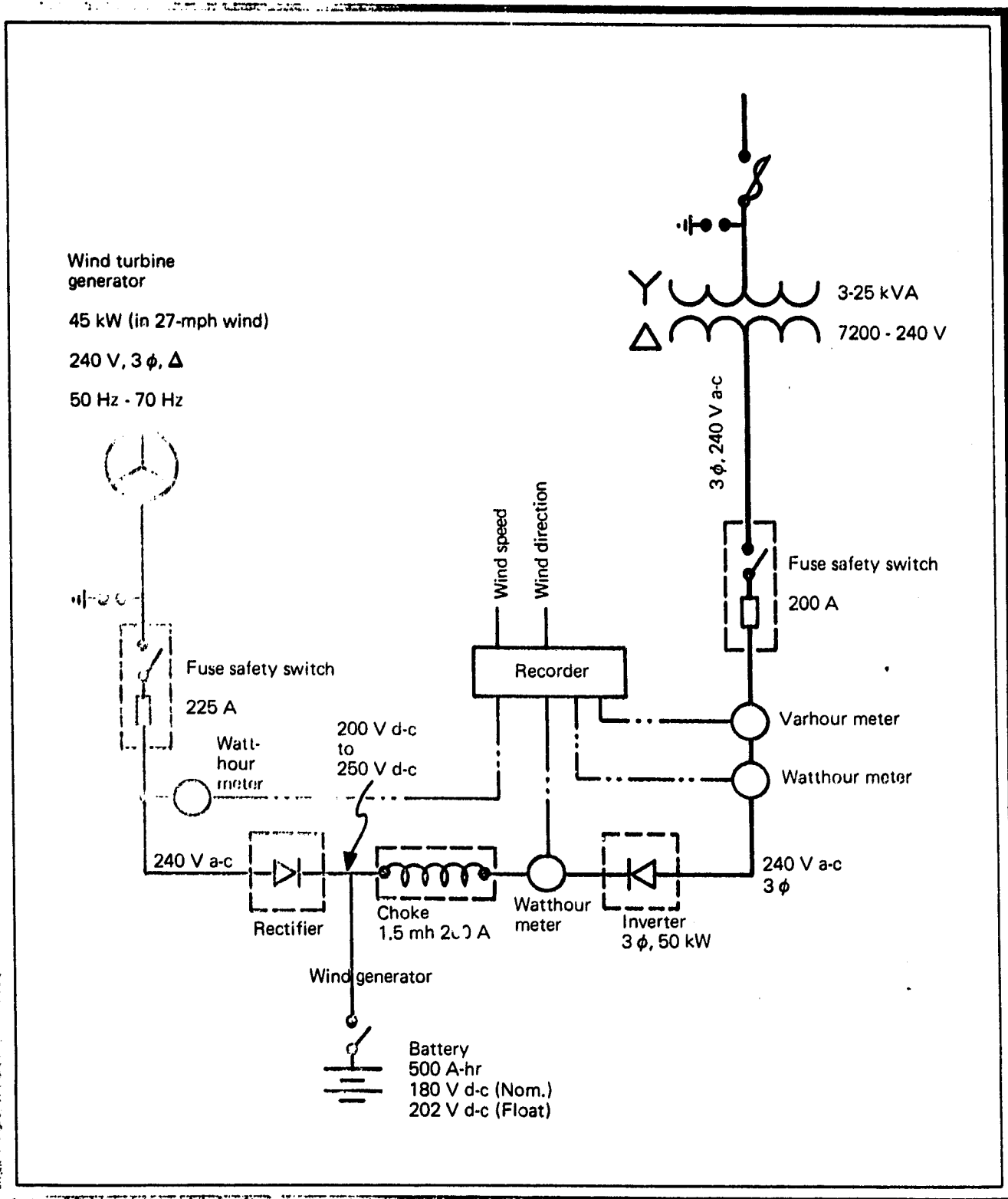
Figure 1. (left) Wind turbine generator at PP&L's Harwood Wind Electric Station has a 45-ft-diam, four-blade rotor design.

Figure 2. (below) PP&L project engineer J. E. Pfluger checks conditions inside the environmentally controlled building at PP&L's Wind Electric Station. The station alarm panel is in the foreground.



POWER FROM THE WIND

Figure 3. Electrical design of PP&L's wind turbine generator system.



service area permitting some cross-checking of test results.

The physical size of the WTG is impressive. Its rotor is 45 ft in diameter and the top of the arc swept by its four 20-in.-wide aluminum blades is 64 ft above the ground. The rotor is mounted on a driveshaft downwind of a compact nacelle that houses drive-shaft bearings, a step-up transmission, an alternator and a fail-safe braking system. The unit is mounted on a pintle at the top of a 40-ft-high cylindrical steel tower and yaws automatically whenever the wind direction changes. This keeps the rotor facing squarely into the wind for maximum conversion efficiency.

High-lift airfoil blades

The four-blade configuration, its most distinctive feature, was dictated by the low average wind velocities here. It captures more wind energy than the two blades found on most WTGs. Because the rotor blades are sophisticated high-lift airfoils similar to the wings of STOL aircraft, the rotor starts turning in a very low wind velocity. Actual cut-in velocity (the wind velocity at which the WTG starts to generate power) is only 6 to 8 mph.

The blades are fabricated by stretching high-density sheet aluminum around three tubular aluminum spars that run the full length of each 180-lb blade. High-strength aircraft rivets hold the skin in place. The advantages

of this blade design are low fabrication cost and a high strength-to-weight ratio. The blades also are flexible so they help to cushion shocks caused by sudden, powerful gusts of wind. They also should be less subject to fatigue cracking than blades of extruded solid aluminum.

Rotor blade pitch (which determines the bite of the blade on the wind) is normally fixed and cannot be adjusted while the wind turbine-generator is operating. It can be manually adjusted at other times, however, to obtain improved wind energy conversion efficiency. When a satisfactory blade pitch for local wind conditions has been established, it is rarely changed.

Because the power in the wind increases with the cube of wind velocity, high winds are desirable when operating a wind turbine-generator—up to a point. PP&L's WTG is designed to operate through a range of wind velocities from 6 to 35 mph. Two fail-safe brakes automatically stop the rotor and lock it in position in higher winds including those of hurricane force. In addition, the tower is designed to withstand winds of that force.

Synchronizing with the system

When operating in a 27-mph wind, the WTG has a rotor speed of 36 rpm. This drives the alternator, through the step-up transmission, at a speed of 1800 rpm at which the alternator produces 240-V, 60-Hz, three-phase power. If the rotor could be kept spinning at 36 rpm at all times, synchronizing the output of the WTG with the PP&L distribution system would be no problem. However, such consistent action is not possible nor do the WTG's fixed blades offer adjustment capabilities to compensate for this. Larger wind turbine-generators that are being developed under Department of Energy (DOE) sponsorship for testing by utilities (see "Megawatts from the Wind," POWER ENGINEERING, March 1976, pp. 64-68), have blade pitch that adjusts automatically when wind velocity varies, thus maintaining constant rotor rpm.

The first step in converting the non-synchronous power output to synchronous power is to rectify the alternating-current output of the WTG to direct current. Output of the rectifier—variable-voltage direct-current power—is then supplied to a synchronous inverter.

The inverter fires pulses of synchronized current into the established PP&L sine-wave current form which is provided through three 25-kVA, single-phase, 7200-to-240-V distribution transformers. Further electrical design details are given in Figure 3.

Wind energy is stored by supplying the direct-current output of the rectifier to a 5400 A-hr storage battery. Output of the storage battery can be supplied to the synchronous inverter when desired so the stored energy can be fed into the distribution system. When the storage battery is used, it helps to regulate the direct-current voltage supplied to the inverter and also helps to level the load applied to the WTG.

Daily on-off status of the WTG is observed and recorded through the radio alarm indications transmitted to the system operator. Shutdowns for lack of wind, unsafe conditions, inverter outages and loss of alternating-current conditions also are observed and recorded. An alarm panel at the wind energy research station helps maintenance personnel to quickly pinpoint the cause of a problem, Figure 2.

Electrical parameters associated with the operation of the WTG are measured with standard company metering equipment. There are watt-hour meters at the alternating-current output of the WTG, and at the direct-current power input and alternating-current power outputs of the inverter. A VAR-hour meter measures the reactive power taken by the inverter and a magnetic tape recorder stores the data on tape, along with wind velocity and direction data. Tapes are collected monthly and the data processed on a PP&L computer. After analyzing the data, utility engineers prepare a monthly performance report.

Tests have broad scope

Engineers are running a variety of tests during the course of the research project. For example, they are checking voltage and current magnitudes, and accompanying wave shapes, under varying load conditions at the output of the WTG, and at the input and output of the inverter. They also are checking the overall efficiency and power factor of the inverter at various power input levels, and watching for radio and TV interference caused by the WTG and inverter. The magnitude and extent of harmonics superimposed on the distribution line by the inverter is being determined. In other tests, the effects of WTG operation on other loads connected to the same power distribution line are being evaluated.

As data are analyzed, PP&L engineers expect to develop a comprehensive profile of WTG performance gained through their unit's two full years of operation. **END**

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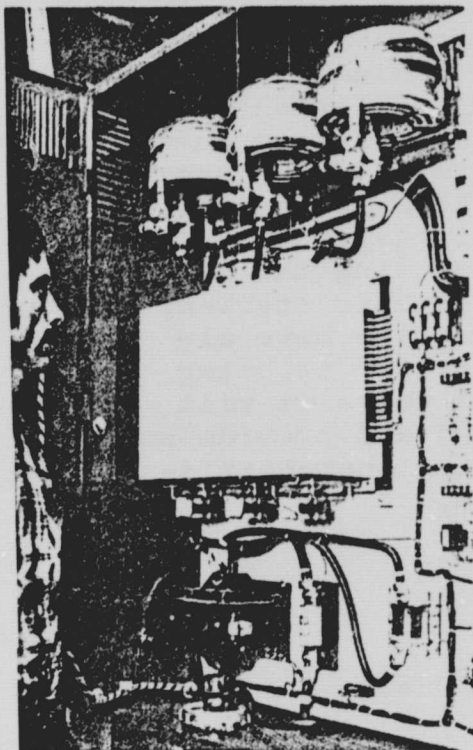


Figure 4. This 50-kW, three-phase, line-commutated inverter synchronizes the output of the WTG to the PP&L system.

OPERATIONAL CHARACTERISTICS OF A 60 KW PHOTOVOLTAIC SYSTEM
INTEGRATED WITH A UTILITY GRID

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U.S. Department of Energy,
Washington, D.C. 20545

Summary

Under the sponsorship of the U.S. Department of Energy, Delta Electronic Control Corporation (DECC) has designed and built a 60 kW photovoltaic power system. The power system will operate from a 60 kW array without energy storage and will produce low-distortion, 480/277 Vac, 60 Hz output to augment a remote utility grid. The program has been initiated and administered by the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia. Tests have been performed on the power conversion system at full power from an array simulator and at 30 kW from the photovoltaic array at the DECC facility. The system has met or exceeded all major specification requirements and has operated, without problems, augmenting the utility grid at DECC since December 1978. The automatic start-up and shut-down controls incorporated into the system have allowed the system to operate unattended. The system is being installed at a remote California military site where it will augment an existing diesel-powered utility grid and provide an average of 10% of the grid power. The operating characteristics of the system are described in this paper.

presented at the
1979 Photovoltaic Solar Energy Conference
Berlin, West Germany
23-26 April, 1979

INTRODUCTION

In 1977 the United States Army Mobility Equipment Research and Development Command, Ft. Belvoir, Virginia, (MERADCOM), initiated a program to design, fabricate, test, install, and evaluate a 60 kW photovoltaic (PV) system. The program is sponsored by the U.S. Department of Energy, Washington, D.C. The primary objective of the program is to demonstrate that a photovoltaic power system without energy storage can effectively augment a remote utility network. The PV system was designed and built by Delta Electronic Control Corporation (DECC), Irvine, California, to MERADCOM specifications. The system has been operating with a partial array since December 1978 and is presently being installed at Mt. Laguna Air Force Station in California where it will augment the existing diesel power plant and generate up to 10% of the average power.

Many of the design characteristics have been discussed in a previous paper (1). The system characteristics are summarized in Table I, and Figure 1 is a block diagram of the system. This paper addresses the operational characteristics of the system.

2. SYSTEM DESCRIPTION

The system consists primarily of the PV array, a paralleling and monitoring panel and a power conditioner. The array is comprised of two different types of PV modules, seriesed and paralleled to provide the optimum input voltage for the inverter. The paralleling and monitoring panel performs the paralleling function and provides means for monitoring the loaded and unloaded operation of individual series strings of PV modules as well as the entire array. The array construction is shown in Figure 2; the paralleling and monitoring panel and power conditioner are shown in Figure 3.

The power conditioner consists of an input voltage limiter, a self-commutated dc-ac inverter, and system control circuitry. The system controls include automatic start-up and shut-down circuitry responsive to the available solar power, peak power tracking circuitry, grid matching circuitry, four-

quadrant output power-flow control circuitry, and fault protection circuitry. Figure 4 is a chart depicting the operation sequencing. The protection circuitry provides shut down with automatic recycling for faults of a temporary nature (such as utility grid aberrations) and shut down requiring manual restart for faults requiring servicing (such as blown fuses).

The paralleling and monitoring panel and the power conditioner both include signal conditioners to provide analog and digital outputs to a data acquisition system. When the data acquisition system is installed, it will provide on-site and stored information on the system as a whole and on the operation of individual strings of solar panels. The data acquisition system will also record meteorologic information including temperature and wind velocity and direction. The data acquisition system has been developed by Energy Control Systems, Manhattan Beach, California.

3. TEST RESULTS

Since December of 1978, the system has been operating at the DECC facility from a partial PV array (up to 30 kW). Because of the short time available for the DECC tests, little has been done to evaluate the performance of the PV array. The array has, however, been subjected to a variety of weather conditions including cell temperatures as low as 4°C, rain, wind driven hail (up to 1 cm in diameter), and 29°C clear days. No deterioration in array performance has been observed.

The primary emphasis of the test performed to date has been on power conditioner and system performance. The system has operated unattended through a variety of insolation conditions ranging from bright sun to inadequate or marginal insolation. The system has cycled on and off automatically as designed, starting up whenever 4 kW array power is available (1.5 kW system output power) and shutting down when the available power has remained less than 2.5 kW (no output power) for more than 8 minutes. The 8 minute delay effectively prevented nuisance shut-downs during marginal insolation. During these winter test months the insolation has been generally low, but on most days there has been adequate insolation for start-

up at some time during the day. Even so, the overall operating efficiency as measured by incorporated input and output kWh meters has been 77%. The efficiency as a function of the system output power is given in Figure 5. The power tracking circuitry has tracked the maximum array power to within 99%.

During the tests, power has been fed into the Southern California Edison utility grid under a co-generation contract with DECC. The photovoltaic power system has caused no observable disturbance to the utility grid. Disturbance of the utility grid at start-up is prevented by increasing the output current from the power conditioner gradually. Figure 6 shows the increase in output current in the unusually stringent case of switching the power conditioner on with 30 kW available from the array. There is no measurable effect on the grid voltage during start-up.

The power conditioner operated properly and without damage through a series of grid abnormalities and interruptions. Additional test data are shown in Table I.

4. CONCLUSIONS

This program has demonstrated that it is possible to produce a multi-kilowatt photovoltaic power system which augments a utility grid and which

- (1) operates from the photovoltaic array without energy storage,
- (2) extracts maximum available power from the PV array,
- (3) provides low-distortion output current,
- (4) operates unattended,
- (5) is protected against variations or losses of the utility grid, and
- (6) is stable in the face of variations in the array output, such as those due to changing or marginal insolation.

The efficiency and stability results are very encouraging and augur well for future systems.

Acknowledgements

The authors wish to acknowledge the support given by the Photovoltaic Branch of the U.S. Department of Energy and the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia.

References

1. D.J. Roesler, "A 60 kW Solar Cell Power System with Peak Power Tracking and Utility Interface," Proceedings of the IEEE Photovoltaic Specialists Conference, 1978, p. 978.

TABLE I. SYSTEM PARAMETERS

SOLAR CELL ARRAY	<u>SITE</u>	
	Latitude	33°N
	Maximum wind velocity	120 knots
	Altitude	1900 meters
	<u>ELECTRICAL CHARACTERISTICS @ 50°C</u>	
	Power	64 kWp
	Voltage	230 Vdc
	Annual output energy	120,000 kWh estimated
	<u>COMPOSITION</u>	
	Solarex Model 9200	756 panels (14 kWp)
	Solar Power Model E-10008	1610 panels (50 kWp)
	Panels/series string	14
POWER CONDITIONER	Number of series strings	169
	Mounting frames	Galvanized steel tubing
	Supports	Wood panels, concrete footings
	Tilt angle	25° (fixed)
	<u>INPUT</u>	
	Operating voltage range	180-290 Vdc
	Maximum input voltage	400 Vdc
	<u>OUTPUT</u>	
	Rated power	60 kW (75 kVA)
	Frequency	60 Hz
SYSTEM	Voltage	277/480 Vac, three phase
	Efficiency	
	At 60 kW	90% specified, 92% measured
	At 30 kW	85% specified, 91% measured
	Current dist. (THD) @ 60kW	3% specified, 1.5% measured
	Power control	Four-quadrant
SYSTEM	<u>FEATURES</u>	
	Start-up and shut-down	Automatic with insolation
	Utility augmentation	Automatic, output VAR control
	Peak power tracking (PPT)	Within 99% (measured)
	System stability	Indep. of PPT response time
	Monitors	Array and conditioner, meters and status indicators
	Local energy storage	None
	Data acquisition system	Microprocessor-based with 196 analog and 52 digital inputs

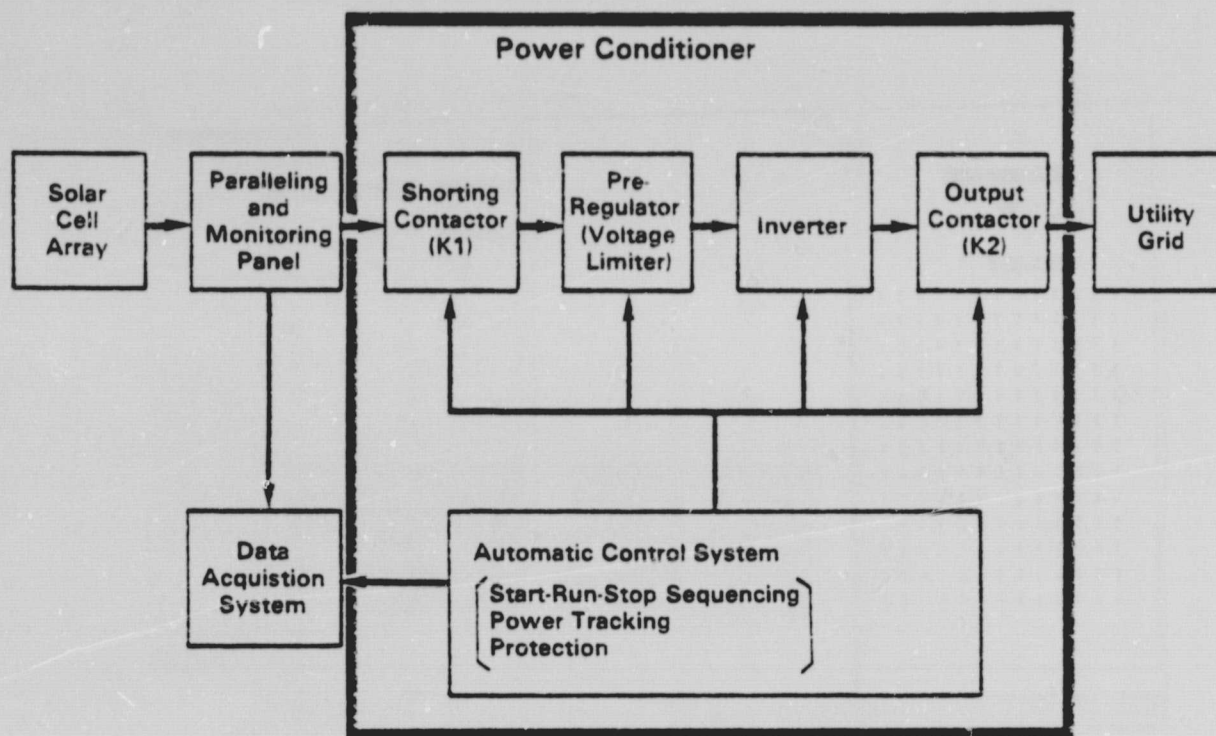


Figure 1. System Block Diagram

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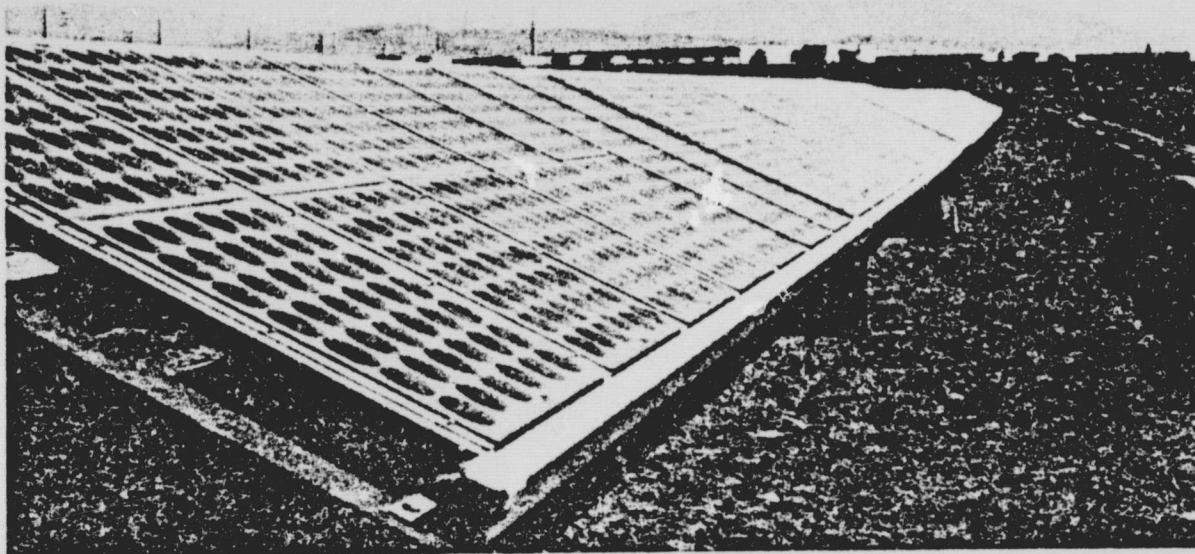


Figure 2. Photovoltaic Array

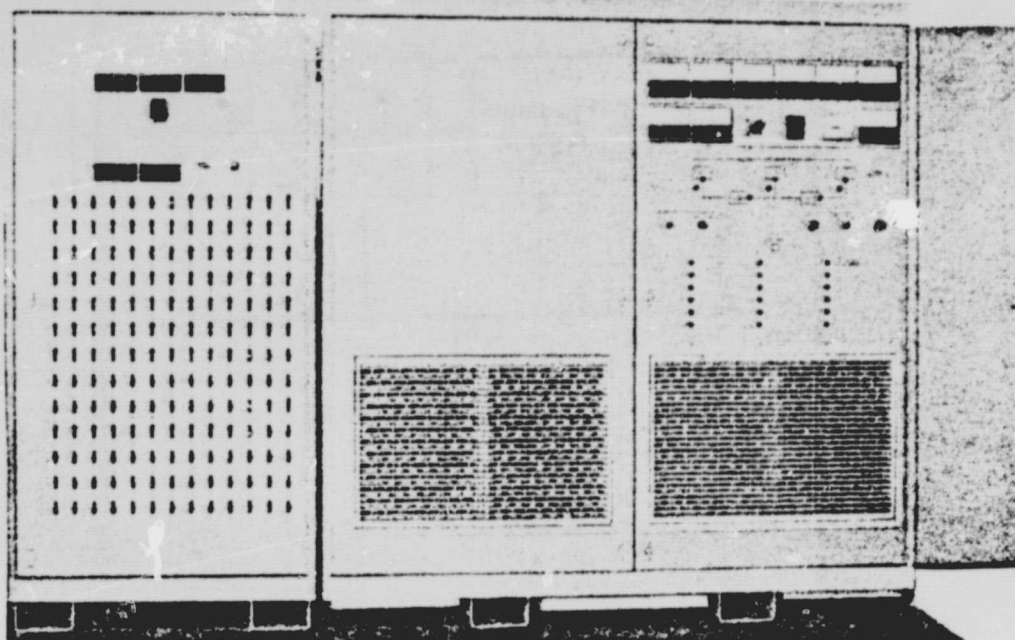


Figure 3. Paralleling and Monitoring Panel
and Power Conditioner

DESCRIPTION	START-UP (≈ 21 sec.)	OPERATION	SHUT-DOWN
STAND-by			
Bias power on			
Array shorted (k1)			
Inverter on			
On line (k2)			
Peak Power tracks			
<u>SHUT-DOWNS</u>			
<u>with Automatic Reset</u>		<u>with Manual Reset</u>	
Insufficient solar power (for more than 8 minutes)		Blown fuse	
Frequency error (± 2 Hz)		DC overvoltage	
Grid/inverter mismatch		Ground current fault	
Remote interlock open		Excessive reverse power	
		Overtemperature	

Figure 4. Operating Sequence

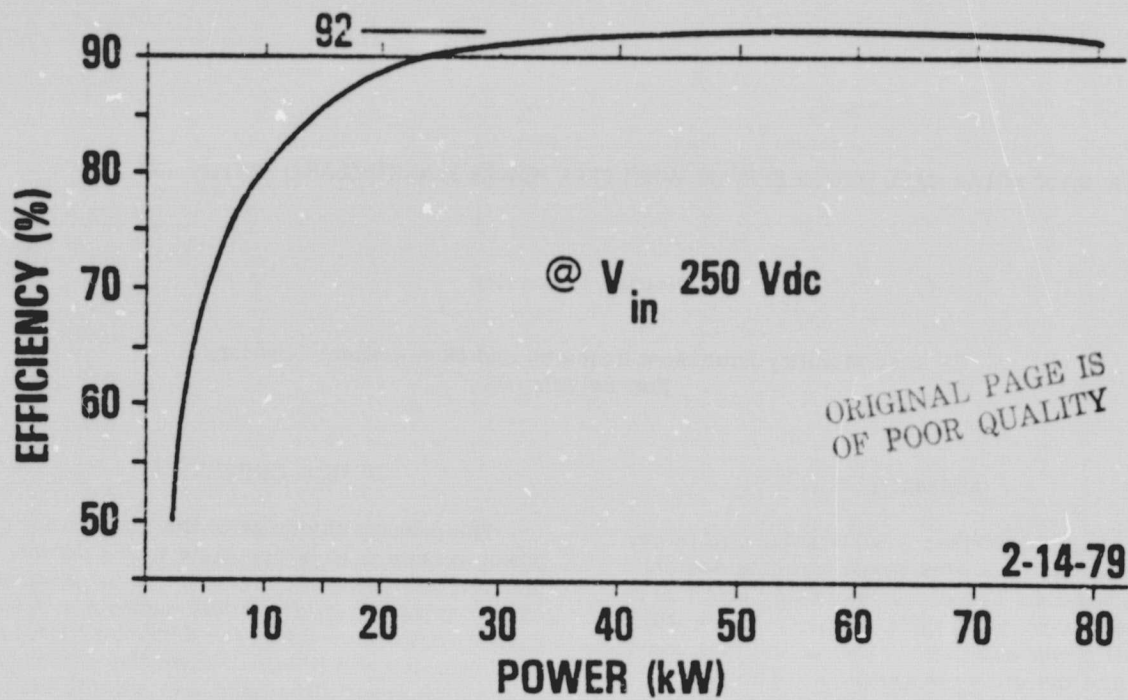


Figure 5. System Efficiency

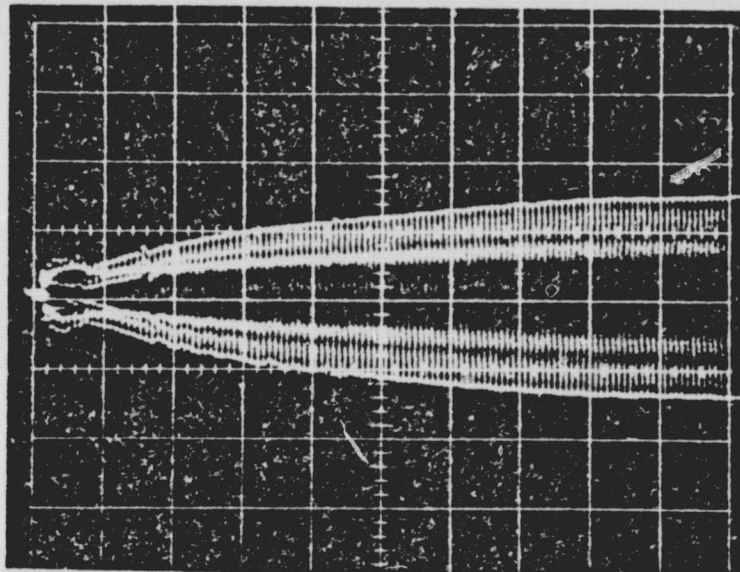


Figure 6. Rate of Rise of Output Current
at Turn-on, 30 kW Array Power Available
Horizontal Scale: 0.2 Seconds Per Division
Vertical Scale: 25 Amps Per Division

A 60kW SOLAR CELL POWER SYSTEM WITH PEAK POWER TRACKING AND UTILITY INTERFACE

Dietrich J. Roesler

US Army Mobility Equipment Research and Development Command
Fort Belvoir, VA

ABSTRACT

This paper describes a 60kW solar cell power system that features peak power tracking and an utility interface. The objective of this effort is to effectively augment a typical utility network with solar cell power and thereby reduce the fuel consumption of the utility power plant. The solar system will not utilize an on-site energy storage. It is planned to produce as much solar power as possible and to feed all the power to the utility.

The 60kW solar cell power system will be designed, fabricated and partially tested during the first eight months of 1978. At that time, this system will be one of the first attempts to actually connect a solar cell power system to an utility network and the findings of this project will have an important influence on future solar cell power systems.

INTRODUCTION

Army applications of terrestrial solar photovoltaic power date back to 1960 when the Signal Corps used two 140 watt arrays at opposite ends of the country to demonstrate solar powered transcontinental voice radio communications.

Currently the Department of Defense, in coordination with the Department of Energy, is engaged in the development of terrestrial applications of solar photovoltaic systems and MERADCOM was assigned program management responsibility for these applications in June 1975. A number of terrestrial photovoltaic systems such as remote instrumentations, radar stations, telephone communications centers, and water purification systems have been built and they have demonstrated the viability of the photovoltaic approach. These systems have provided MERADCOM with a technical base for the development of larger systems. The first large scale terrestrial application, the 60kW solar cell power augmentation system is being developed at present and will be operational in the first part of 1979.

DESIGN OBJECTIVES

The primary objective of the 60kW solar cell power system is to demonstrate that a dc-ac photovoltaic energy conversion system without energy storage can effectively augment a remote military power network. The demonstration is hardware oriented and it will uncover the extent to which a photovoltaic system can provide reliable power with subsequent savings in fuel. In addition, it will identify requirements in system operation, maintenance, and personnel training and will provide operational cost data. These are not generally available from analytic studies.

SYSTEM DESCRIPTION

General

The 60kW solar cell power system will be installed at the Mt. Laguna Air Force Station in California. The system will augment an existing diesel power plant with an average load of about 750kW. The diesel power plant has a total capacity of 2050kW; they have six diesel generators rated at 300kW each and one diesel generator rated at 250kW. Three of the generators run continuously for 24 hours per day, seven days per week.

The solar cell power plant can generate up to 10% of the average load of the diesel power plant and it is anticipated that an equivalent amount of fuel can be saved. Figure 1 shows a block diagram of the solar cell power system. It consists of a solar cell array, a paralleling and monitoring panel, measuring and monitoring instruments, control and protection devices, interconnecting cables and a dc to ac inverter. The inverter is connected by cables to the diesel generator power plant. In this configuration, the power plant will provide for high motor starting currents and back up power.

A summary of the important system parameters is listed in Table 1.

The Solar Cell Array

To furnish the rated peak power of 60kW, the solar cell array uses 1610 modules produced by Solar Power, and 756 modules produced by Solarex. The modules differ in almost all parameters, including electrical output and physical dimensions. The solar cell modules are being procured by the Jet Propulsion Laboratory as part of their Low-Cost Silicon Solar Array Program. The design voltage for the array was selected to 230Vdc. To obtain this voltage, 14 modules have to be connected in series. Each group of 14 modules in series is called a string and the corresponding dc voltage is called the string voltage. Based on the number of modules, a total of 169 strings are in the array. The support structures (frames) are different for each type of module. The frames for the Solarex modules were designed to hold one string or 14 modules. The frames for the Solar Power modules were designed to hold 1/2 string or 7 modules. The design objectives for the frames are low cost, easy transportability and easy installation. Figure 2 shows each type of assembled frame. Each module is protected by a diode connected in reverse across the dc terminals. The diode serves two related purposes; it protects a malfunctioning or occluded panel from the high voltage generated by the rest of the string and it provides an alternate current path so that one defunct panel will not necessarily disable the entire string. The various strings are brought into Row Terminal boxes, situated in the center of each row. The Row Terminal boxes contain surge suppressors connected between each side of each string and ground for protection against lightning-induced voltages.

There are 284 frames in the array, 230 for Solar Power modules and 54 for Solarex modules. It is planned to install these frames on cement pillars in such a fashion that they face south and that their tilt angle from the horizontal is 25°. The tilt angle has been determined by a computer program (developed by Sandia) which calculates the optimum fixed tilt angle for a latitude of 32.5°. Optimum tilt angle in this case is the angle that will yield the maximum energy over the entire year. Figure 3 shows the outcome of this program. The details of the frame installation are shown in Figure 4. Except for the end pillars, every pillar supports two frames. The frames are made of steel which is hot dipped galvanized for corrosion protection. The frames holding the 14 Solarex modules weigh 293 lbs each and the frames holding the 7 Solar Power modules weigh 203 lbs each. The frames will be installed in an area covering 170' by 190'. The row spacing of the frames is 8 feet. This spacing will ensure minimum shading during the operational time. The frames when installed in the array field can withstand wind forces up to 120 knots.

The Paralleling and Monitoring Panel (PMP)

The individual outputs of all 169 strings will be passed through the Row Terminal boxes to the Paralleling and Monitoring Panel. Figure 5 shows the electrical schematic of the PMP. The PMP will be located adjacent to the inverter. Each string is connected to a common bus bar via a fuse, a diode, and a switch. The switch will allow any single string to be disconnected from the common bus bar for evaluation and/or maintenance purposes. Four different measurements can be performed: open circuit, short circuit and two load points. Shunt resistors on the negative side of the strings allow for addition of an automatic data acquisition system. The circuit breaker C1, isolates the array from the inverter. Contactor K1, shorts out the array for test purposes and during the time when the generated power from the array is less than 6 kW.

The high number of strings (169) gives the system a high reliability. In the case one string fails, less than 1% of the total power is lost, and the operation will not be disturbed. Any maintenance required is not critical and can be performed during "no-sunshine" time.

The Array Simulator

A voltage-limited current-source array simulator will be built for use with the inverter. This simulator will provide a means of testing the inverter before the array installation is completed and as a source for fault isolation or evaluation of the inverter during array down-time, e.g., at night. The array simulator is located in the PMP.

The Inverter

The inverter is based on a proven high efficient (>90%) 75KVA uninterruptible power supply version. The inverter has two power stages; the dc-dc input stage and the dc-ac output stage. The dc-dc stage will only act as a voltage limiter for the dc-ac stage and is, therefore, very efficient. Figure 6 shows the relationship of array power and corresponding voltage to the insolation and the cell temperature. Based on this Figure, the inverter input stage has to accept voltages in the range of 200 to 400 Vdc.

The dc-ac stage converts the dc input to the 60 Hz sine wave output. Twelve self commutated SCR bridge circuits generate a twelve-step sine wave approximation. The lowest order harmonic generated is the 11th, and minimal filtering is required to ensure total harmonic distortion of less than 3%. The inverter is connected to the diesel power plant through an impedance cushioning. The

inverter is also designed to extract maximum or peak power from the solar array and to feed this power to the utility grid. This feature will be accomplished by the peak power tracker. The peak power tracking logic utilizes a reference signal that is proportional to the array power and a modulated control voltage to determine on which side of the power curve the operating point is located. The peak power point occurs when the tangent on the power curve in Figure 6 is horizontal or when $\Delta p/\Delta V = 0$. This is the point to which the load will be adjusted. The inverter is capable of varying the amplitude and the phase angle of its output voltage. This feature gives the inverter a great flexibility and together with impedance cushioning makes the interface with an utility network possible. Figure 7 shows a schematic of the inverter.

The application of this inverter differs from the usual application in two significant ways. The solar array is not a voltage source, but more nearly approximates a voltage-limited current source. The current is determined by such factors as insolation and array temperature. In addition, the output voltage of the inverter is established by connection with the utility line. In this application, the modulation index will determine the dc input voltage to the inverter stage. This voltage will be adjusted by the peak power tracking circuitry to provide the maximum inverter output power available at the particular level of insolation and array temperature.

Meters are provided to monitor the inverter output voltage, current, frequency and elapsed time. Additional meters monitor the power, watt-hours, and VAR into the net.

Operation and Utility Interface

The operation of the solar array and power conversion system is automatic. As the array output power increases and the output voltage of the inverter reaches that of the utility line, the output from the inverter will automatically be phase locked to the utility line and the inverter will be connected to the net. At this point there is no power transmitted to the net. As the available power from the array increases further, power will be delivered to the net and the solar cell power system will augment the net. If the output power from the array decreases sufficiently, there will eventually be a negative power flow, i.e., from the net into the inverter. The design of the system limits this negative flow to the power losses (less than 3000W) of the inverter. If the negative power flow persists for more than a few minutes, the inverter will be isolated from the net until the output voltage of the inverter again equals the utility line voltage.

The utility interface utilizes three main

parameters; impedance cushioning, and phase and voltage control of the inverter output. By controlling these parameters, a smooth power transfer is ensured.

Data Acquisition System

The system has been designed to accommodate a data acquisition system. All of the system data signals are available in the paralleling and monitoring panel. It is planned to utilize a small on-site acquisition system consisting of a minicomputer, a video monitor, a printer, and a tape storage. The following data will be collected on tape and made available upon interrogation.

- The current of all 169 strings
- The input voltage to the inverter
- The watt-hours generated in the array
- The watt-hours delivered to the power plant
- Ambient temperature, insolation, windspeed, and wind direction.

The data will be measured hourly during the time of operation. Abnormalities in the operation will be flagged whenever they occur.

CONCLUSION

The 60kW solar power augmentation project is an important step in the development of photovoltaic systems, especially for those which will interface with utility power grids. When in operation, this system will uncover problems connected with operation and the maintenance and it will provide the required feedback for other, larger systems planned in the future. Figure 8 shows an artist's concept of this system and it is anticipated that this artist's concept will become reality in the latter part of 1978.

ACKNOWLEDGEMENT

The author wishes to acknowledge the support given by Sandia Laboratories for the array analysis and by Delta Electronic Control Corporation for the detailed system design and construction. This project is part of the Military Applications of Photovoltaic Systems and sponsored by the US Department of Energy. Dr. Harold Macomber is the DoE Program Manager.

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SOLAR CELL ARRAY	POWER [KW]	60
	VOLTAGE [Vdc]	230
	CURRENT [Adc]	261
	CELL TEMP. [°C]	50
	PANELS PER STRING	14
	NUMBER OF SOLAREX PANELS	756
	NUMBER OF SOLAR POWER PANELS	1610
	NUMBER OF PARALLEL STRINGS	169
POWER CONDITIONER	POWER [KVA]	75
	FREQUENCY	60Hz
	OUTPUT VOLTAGE [V]	277/480, 3 PHASES
	EFFICIENCY, F.L. [%]	90
	TOTAL HARMONIC DISTORTION	LESS THAN 3%
	PHASE ANGLE	120° ± 1%
	OPERATION	AUTOMATIC STARTUP AND SYNCHRONIZATION; PEAK POWER TRACKING
	MODES	a. CONNECTED TO UTILITY GRID b. STAND ALONE

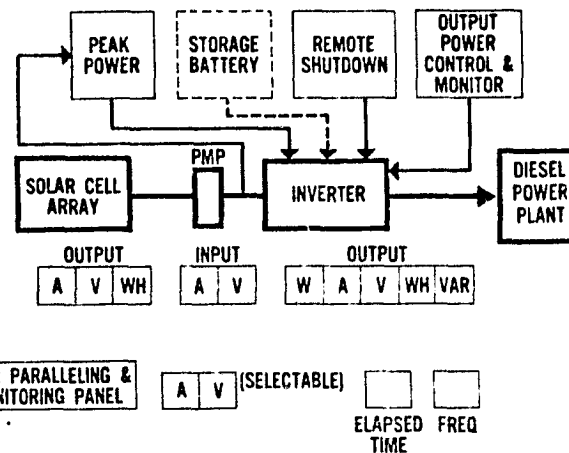


Table 1 System Parameters

Figure 1 Block Diagram of System

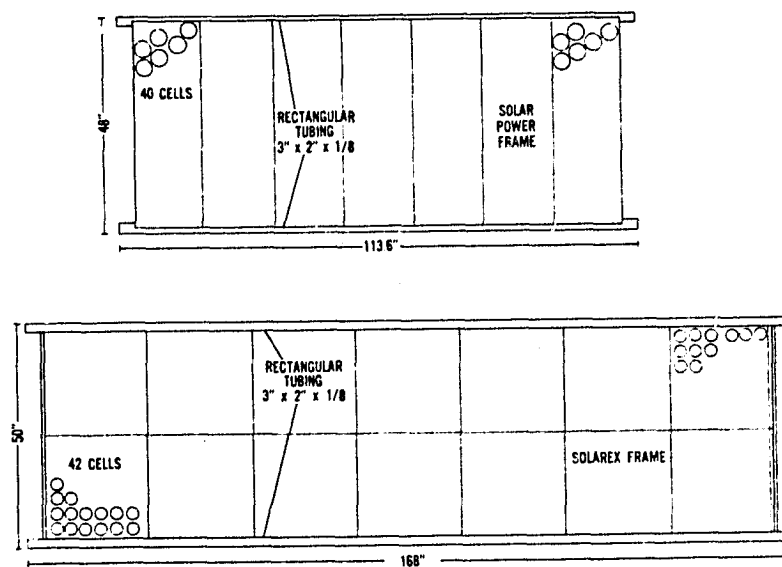


Figure 2 Solar Power and Solarex Frame Assembly

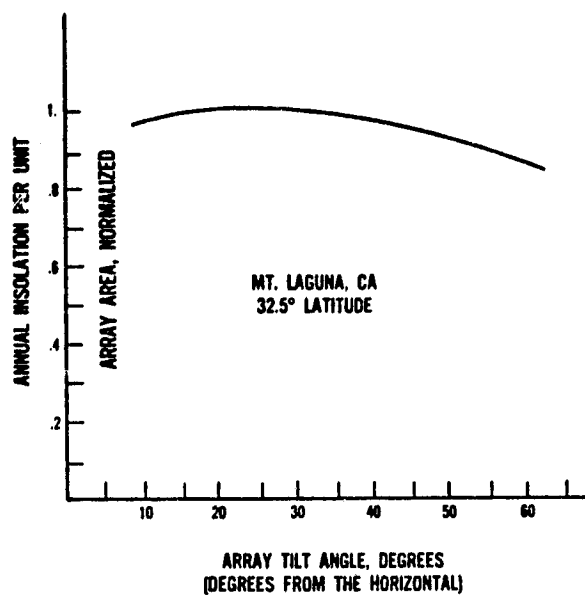


Figure 3 Determination of Tilt Angle

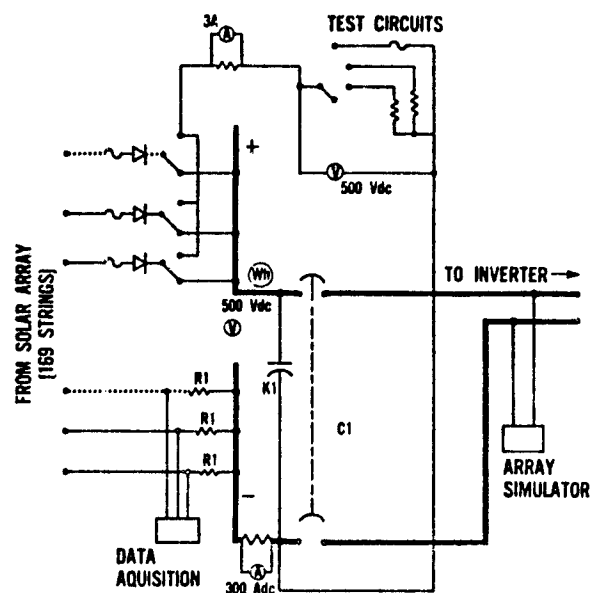


Figure 5 Paralleling and Monitoring Schematic

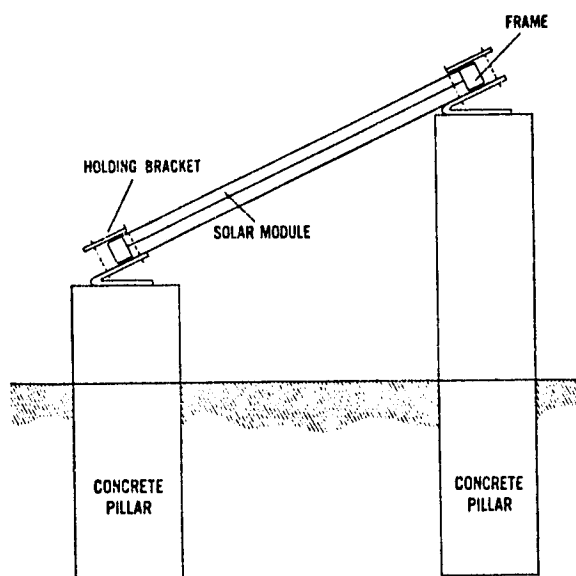


Figure 4 Frame Installation

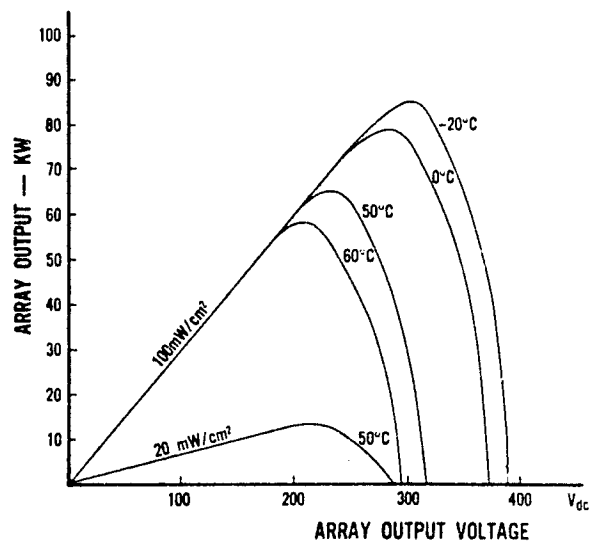


Figure 6 Temperature Effect on Array Power and Voltage

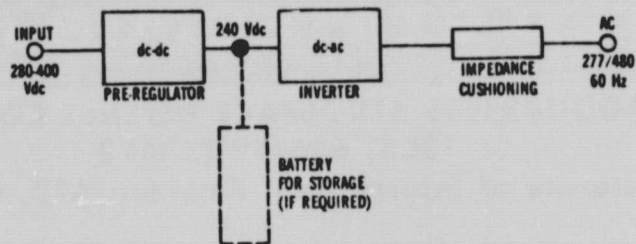


Figure 7 Schematic of Inverter

60 KW PHOTOVOLTAIC (SOLAR) AUGMENTATION SYSTEM

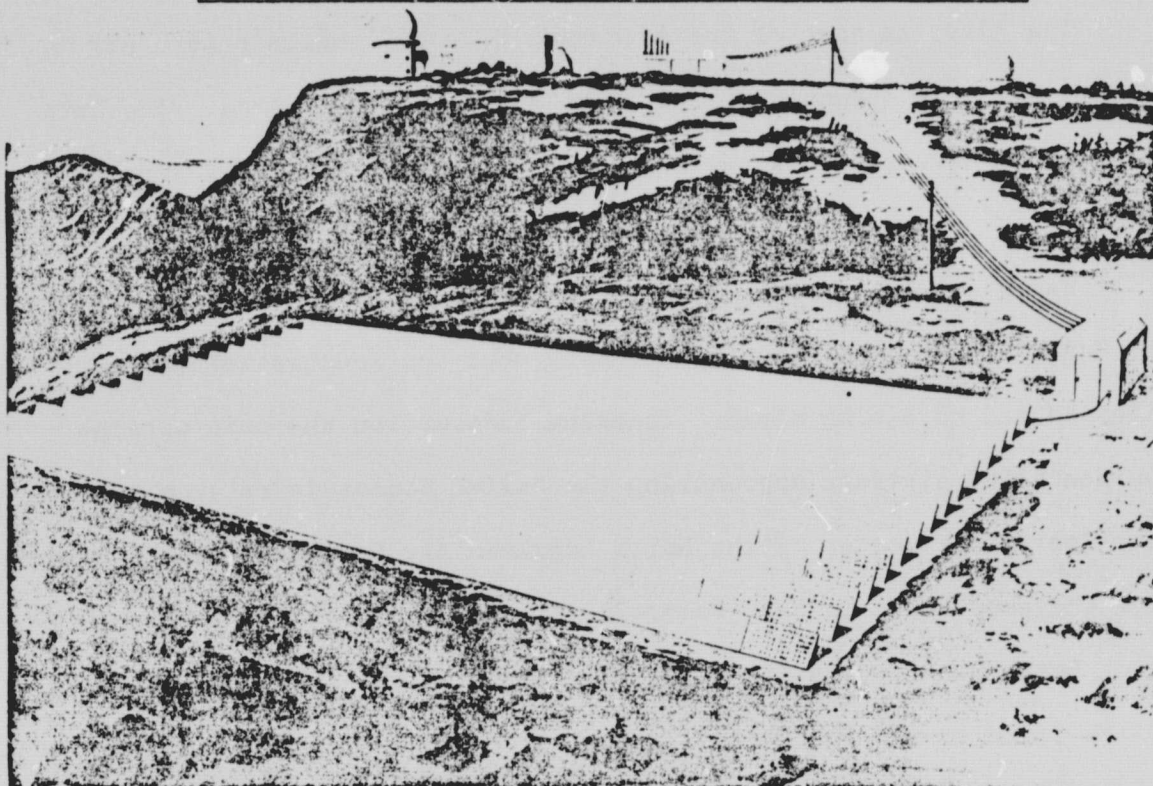


Figure 8 Artist's Concept of System Installation at Mt. Laguna



FACT SHEET

UNITED STATES AIR FORCE

HEADQUARTERS AEROSPACE DEFENSE COMMAND

(303) 635-8911/3523

Directorate of Information, Peterson AFB, CO. 80914

MT LAGUNA AIR FORCE STATION, CALIFORNIA

Mt. Laguna Air Force Station, about 60 miles east of San Diego on a 6,000-foot peak in the Cleveland National Forest, is the home of the Air Force's 751st Radar Squadron and Detachment 4, 14th Missile Warning Squadron.

The 751st is part of the Aerospace Defense Command's 26th Air Division, which is headquartered at Luke Air Force Base, Ariz. The 26th maintains forces for air surveillance and air defense of the southwest United States.

Using various types of radars and computerized equipment, the 751st Radar Squadron watches the airspace over the southwestern part of California and adjoining areas. Tracking information the unit obtains on unidentified aircraft approaching the United States is relayed to the Combat Operations Center of the North American Air Defense Command, housed inside Cheyenne Mountain near Colorado Springs.

Detachment 4 uses its radar to search for sea-launched ballistic missiles fired toward the United States. That data also would be sent to the NORAD Combat Operations Center.

(MORE)

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Mt. Laguna is one of the Aerospace Defense Command's radar stations that is scheduled to be turned over to the Federal Aviation Administration for operations as part of the new Joint Surveillance System. Radars in the new network will be jointly used by the FAA for civil air traffic control and by the air defense system for air surveillance in peacetime.

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For additional information, contact: Major Jerry C. Hix
Information Office
Peterson AFB CO 80914
(303) 635-8911, Ext. 3523

DOE NEWS:

FOR IMMEDIATE RELEASE
August 15, 1979

WORLD'S LARGEST SOLAR CELL ELECTRIC POWER STATION ACTIVATED

Mt. Laguna AFS, Calif...The day when the sun will supply a significant share of electricity for our nation's homes, offices and factories is still a long way off. But, for the 141 men and women stationed at Mt. Laguna Air Force Station, Calif., living and working in the shadow of the solar electric future is now an everyday occurrence.

Today, federal and military officials activated the world's largest solar photovoltaic power station during dedication ceremonies at the mountain top radar installation, 60 miles east of San Diego.

Funded primarily by the U.S. Department of Energy (DOE), the new 60 kilowatt (kW) solar cell electric power system augments an existing diesel oil fueled power plant operated by the military. The system is expected to supply 10 percent of the electrical power used at the radar station during the day, or, by comparison, sufficient energy to meet the needs of 10 average families.

The project, managed by the U.S. Army's Mobility Equipment Research and Development Command (MERADCOM), headquartered at Fort Belvoir, Va., is part of a joint U.S. Department of Defense DOD/DOE solar energy research program. The principal goal of the DOD/DOE Military Applications of Photovoltaic Systems (MAPS) program is to develop solar electric power systems which can serve as a power source for a wide variety of military equipment and installations, as well as commercial applications.

Simple, Solid-State Device

"Conversion of visible sunlight into electrical energy by solar cells is a direct spin-off of the U.S. satellite and space program," said Joseph La Grone, manager, San Francisco Operations Office, Department of Energy. "This simple, solid-state device holds the promise of long operating life with little need for servicing or maintenance."

"President Carter has called on the nation to meet 20 percent of its energy needs with solar and other renewable resources by the end of the year 2000; solar cells are expected to contribute greatly toward meeting that goal," added George Marienthal, deputy assistant secretary of defense for energy, environment and

and safety. "The Department of Defense is very active in solar energy. We have more than 100 solar projects in operation or under construction."

Solar electric power systems have seen important, if not dramatic, growth during the past few years. The cost of solar cells, measured in peak watts, was \$30 per peak watt in 1975; today, it is down to \$8 per peak watt. DOE hopes to see that price drop to \$.70 per peak watt by 1986, at which time electricity generated by the sun will become competitive in many areas with other more conventional power sources.

Cost of Mt. Laguna solar electric power station is \$1.6 million, a price tag which includes the purchase of solar cell modules at 1977 prices. Researchers believe that, should a similar power station begin construction today, overall system costs would be approximately 40 percent less. Given time, such systems might be constructed for less than \$100,000.

The heart of the Mt. Laguna power system is its half-acre array field, consisting of 2,366 photovoltaic power modules, a total of nearly 97,000 individual solar cells. The modules are grouped in panels and mounted on 18 rows of wood and metal frames.

Operation of the 60 kW system, including its state-of-the-art power conversion equipment, is completely automatic. As the sun rises in the morning, and power levels increase to about 5 percent of its capacity, the system automatically connects itself to the electrical grid, matching the characteristics of the diesel power plant. When power from the array decreases, either because of heavy cloud cover or darkness, the system disconnects itself, until power levels once again are sufficient to activate the start-up cycle. Because of the system's design application, there is no battery storage capacity as is found in other typical solar electric applications.

Reliable Power With Savings in Fuel

The primary objective of the system is to demonstrate that a direct current (dc) to alternate current (ac) solar cell power system without energy storage can effectively augment a remote power network, providing reliable power with a subsequent savings in fuel. Researchers predict that the Mt. Laguna system will save an average 31½ gallons of diesel fuel daily, or an estimated total of 11,500 gallons annually.

"We expected to achieve benefits from this large-scale experiment far beyond the savings of petroleum fuel," commented Donald Faehn, head of the Defense Photovoltaic Program Office at MERADCOM. "We will continually assess the operation and maintenance requirements. In this way, we'll obtain information not always available from analytic studies. This will help designers of future photovoltaic systems for civilian as well as military applications."

Although 60 kW is small by electric utility standards, Mt. Laguna is one of the first experimental steps leading to larger applications of solar electric generating systems. These applications may include shopping centers, factories, residential clusters, other DOE applications, and in the far term, utility power stations.

The Mt. Laguna project is the culmination of the MAPS program's initial four-year test and demonstration program. Earlier military demonstration projects included photovoltaic systems for remote instrumentations, a radar station, telephone communication center and remote water purification system. These systems were peak power rated at 35 watts to 10.8 kW.

Prime contractor for the Mt. Laguna project is Delta Electronic Control Corporation, Irvine, Calif. Solar cell modules were manufactured by Solar Power Corporation and Solarex Corporation.

-30-

EDITOR'S NOTE: Public access to the Mt. Laguna AFS solar electric power station is restricted. For clearance to visit the site after August 15, please contact Captain Roy Ash or Lieutenant Maureen Wortham, Mt. Laguna AFS, Calif. 92048; telephone (714)442-0347, Ext. 323.

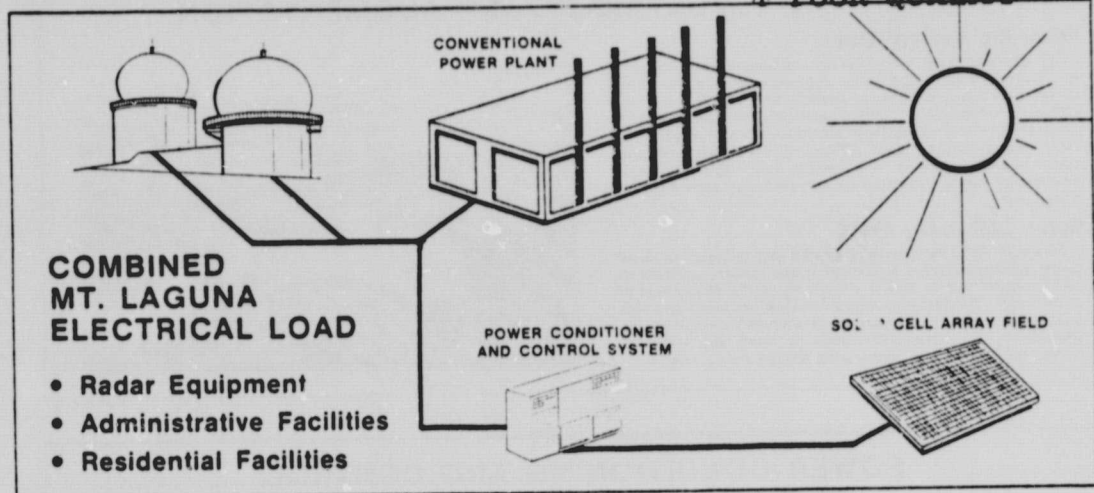
FOR FURTHER INFORMATION CONTACT:

Hank Bowden
DOE
(415)273-4135

or

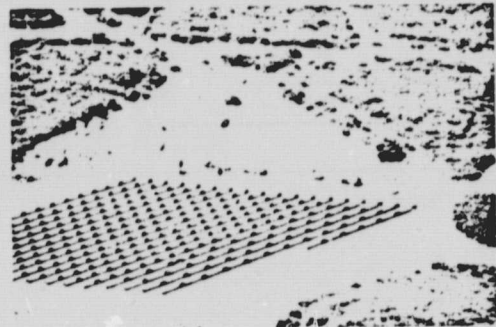
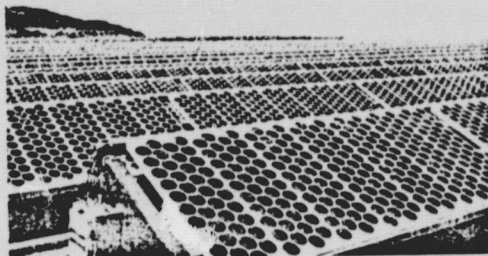
Eugene Osolinsky
MERADCOM
(703)664-5598

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The Mt. Laguna photovoltaic power generation facility became the world's largest application of solar cell equipment when installation was completed in June 1979.

It was made possible through a cooperative program between the Department of Defense and the Department of Energy known as Military Applications of Photovoltaic Systems. The project was managed by the Defense Photovoltaic Program Office, US Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia, in cooperation with the USAF Aerospace Defense Command.



**Solar Cell
Electric Power**



MT. LAGUNA AIR FORCE STATION, CALIFORNIA

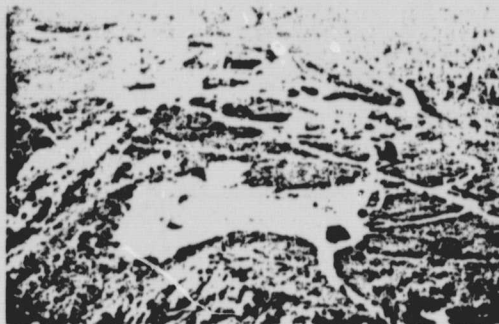
SOLAR PHOTOVOLTAIC POWER AUGMENTATION

What the System Does

The 60 kW solar cell power system installed at the Mt. Laguna Air Force Station in California augments an existing diesel power plant which supplies an average load of about 750 kW, continuous. The solar cell power plant can generate up to 10% of the average load of the diesel power plant. The nominal array power rating is 60 kW peak. Operation of the solar array and power conversion system is automatic, requiring no operator intervention during daily start-up and shutdown each morning and evening.

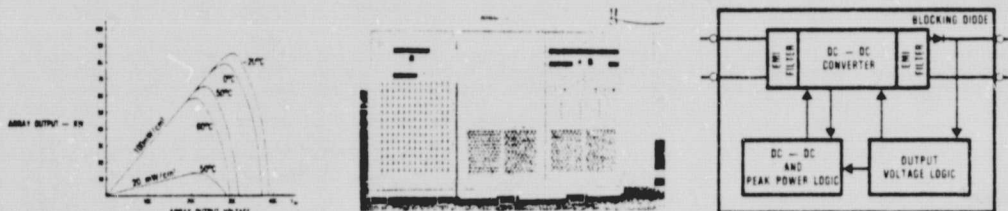
Solar Cell Array Field

This solar cell array (which interfaces with the existing diesel power generating plant at the Air Force Station) consists of 12,000 square feet of panels, occupying 32,000 square feet of ground area. The panels contain 2,366 solar cell modules which were provided by two manufacturers under contract to the Department of Energy. The array is tilted 25° from the horizontal for maximum year-round energy production.

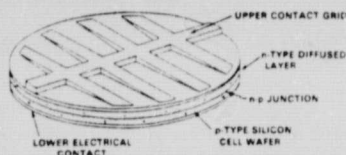


POWER CONDITIONING AND CONTROL

An important part of this solar energy system is the power conditioner, which converts direct current from the solar array to alternating current at the precise voltage, phase, and frequency to match the Station's 480 volt, three-phase power from the diesel generator plant. The design for the power conditioner was adapted from a commercial solid state 75 kVa inverter which is used for uninterruptible power applications. This component provides the functions of automatic start-up and shutdown each morning and evening, and is the main interface with the data acquisition system. In addition, it constantly adjusts the solar array dc voltage to the optimum level so that maximum available power is extracted from the array at all times. This feature is referred to as "maximum power tracking" and is effective over the entire range of solar radiation and ambient temperatures to be encountered.



What Photovoltaics Are



Photovoltaic Process

Solar cell power systems convert sunlight directly to electricity. The conversion of sunlight (photons) to electricity is accomplished through what is known as the photovoltaic effect. This effect occurs when sunlight strikes certain semiconductor materials (e.g. silicon) and is absorbed by atoms of these materials. This causes electrons to escape from their energy levels and allows conduction of electric charges in these materials. The completion of a circuit through contact grids on the front and back of the cell causes current to flow and electrical power is generated.

Photovoltaic cells may be connected in series and/or parallel combinations to produce the voltage and current needed for specific applications.

Mt. Laguna

The Mt. Laguna Air Force Station, home of the USAF Aerospace Defense Command's 751st Radar Squadron, is located on top of Mt. Laguna approximately 60 miles east of San Diego, California on lands within the Cleveland National Forest, administered by the US Department of Agriculture. Approximately 200 civilian, military, and Federal Aviation Administration personnel occupy the station and the radar installations. Facilities include command and administration buildings, residential complexes, water and sewage systems, electrical power generation and utility line network.

Looking Ahead

The Department of Defense in cooperation with the Department of Energy, is currently engaged in demonstrating the utility of photovoltaic (P/V) systems through the Military Applications of Photovoltaic Systems (MAPS) Program. This program encompasses the development and operation of several photovoltaic system demonstration projects, and is being administered for DOD by the US Army Mobility Equipment Research and Development Command.

The objective of the overall program is twofold, representing the respective interests of both the Defense and Energy Departments: First, to stimulate a latent market for solar cell systems within DOD, thereby accelerating industry growth and supporting reduced unit costs, and second, to explore the feasibility of solar cell applications in providing:

- (1) Cost savings by reduced use and storage of petroleum products
- (2) Decreased logistical burdens in the allocation and supply of conventional fuels
- (3) Increased self-sufficiency to remote or isolated military applications

The MAPS Program has already demonstrated the viability of P/V systems when used to power remote instrumentation, radar stations, and to provide personnel services such as water purification. The use of P/V systems in these applications provide reliable power that is economically competitive with the standard power source, usually small generators.

While today's cost of solar cell equipment is not competitive with large diesel power plants of the scale of Mt. Laguna, a vigorous research and development program is underway at the Department of Energy to make these systems economically attractive in the next few years. The experience being gained at this facility will provide a foundation for widespread use of economic and reliable solar cell power at remote military bases, and numerous applications in the private sector.

Cogeneration to save Rohr \$90,000 a year

By Irwin Stambler, West Coast Editor

Utility-owned cogeneration plant, powered by an 800-Kw gas turbine generator, has a net heat rate of 4825 Btu per kw-hr — can sell process steam to Rohr Industries at bargain rates while generating electricity for the grid.

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OF POOR QUALITY

Earlier this year, Rohr Industries entered into a contract agreement with San Diego Gas & Electric to buy process steam from a utility-owned cogeneration plant at a lower price than Rohr is now paying to generate its own steam.

Cogeneration plant is designed around a Solar "Saturn" gen set, ISO base rated at 800 Kw, exhausting into a Deltak heat recovery boiler sized to produce up to 7000 lbs of steam per hour at 15 psi. Presently being built on land leased next to Rohr's facility in Chula Vista — should be completed in time for commercial operation by March 1978.

Installed cost of the plant is pegged at about \$850,000 — for the gas turbine generator, boiler, underground fuel oil storage, controls, piping, etc. In return:

□ **52.6% Net Efficiency.** At 100 per cent base load output, i.e. generating 800 Kw of power and 7000 lbs of steam, plant will operate with a net heat rate of 4825 Btu per kw-hr — or 52.6% efficiency.

□ **\$90,000 Annual Savings.** Without having to make any investment Rohr figures to save about \$90,000 a year in steam costs — by buying steam from the utility rather than generate its own — plus save on boiler maintenance and operation.

□ **Blackout Protection.** Rohr will continue to buy electric power from the utility at regular rates but has a tie-in with the cogeneration plant so that, in the event of a utility power failure, electrical load will automatically be transferred over to the gas turbine generator.

San Diego Gas & Electric favors the concept of utility-owned and operated cogeneration plants located on or next to customer premises — where it can sell the waste heat energy and keep the electricity — rather than become involved with customer-owned facilities.

In keeping with this philosophy, the utility has set up a subsidiary company, Applied Energy Inc., to concentrate ex-

clusively on working out cogeneration arrangements with industrial customers and to help them evaluate their needs and options. Overall program management of the Rohr installation, for example, is being handled by Applied Energy.

The facility meets the general definition of cogeneration, says AE project engineer Michael Hale, since it has been designed from the start to generate electricity — while using the waste heat to generate steam for Rohr's metal processing operations for preparing parts for anodizing, plating, and the like.

Applied Energy is leasing the land next to Rohr's plant where the cogeneration plant is being built. But the installation will belong to SDG&E who will feed the electric power into its normal grid and will charge Rohr for the steam.

"In operation," says Hale, "the turbine exhaust will go through a heat recovery boiler to produce a maximum of about 7,000 lbs of steam per hour at 15 psi. That low pressure permits us to make it an unmanned facility with monitoring accomplished by telemetering information back to our Station B power plant in downtown San Diego."

Though all the steam will go to Rohr, under normal conditions, there will be no change in the way Rohr receives its electric power from SDG&E. As Hale describes it, "the generator output is tied into the regular utility grid and becomes firm capacity. As far as Rohr is concerned, it continues to buy power through the same meter it did before."

However, Rohr does have first call on the turbine generator output in case of emergency. "That's something I've been suggesting to utilities who may become involved in cogeneration as worth looking into," says Hale.

In the initial proposal, SDG&E made no provision for emergency needs of Rohr. But the company came back and said it did not make sense to have a generator system right beside its fence and not be able to hook it back up critical

operations. So SDG&E agreed to put in a second breaker and meter inter-tied with the main one.

In case of a utility failure, the breaker will transfer Rohr's load to the gas turbine system. The arrangement is such that when one line is open the other is always closed and vice versa.

For the extra bus, Rohr pays in two ways. One is in extra capital costs and the other a standby fee. "The latter," says Hale, "is like fire protection. You hope you'll never need it, but you want it available just in case." The main consideration as far as Rohr is concerned is insuring the 650 Kw required to prevent any interruption in operation of its computer system.

The pacing item in system design is Rohr's steam needs. Based on cost projections, the appealing thing to Rohr is that it will pay less for steam with the new installation than it did using conventional boilers. Some of these existing boilers will be retained on cold standby condition so they can be brought on line for outages, during turbine generator maintenance, etc.

Hale stresses that the turbine output will be controlled essentially by the steam demand. "While 800 Kw is the maximum output, the varying steam requirements of Rohr will dictate an output range between 400 Kw and 800 Kw. However, the system will be capable of operating in a mode where steam demand is low and the electrical requirements are our primary concern. In that case, the unit can put out a full 800 Kw and steam production would be controlled with a bypass arrangement. Bypassing unneeded exhaust flow allows the unit to operate as a peaking system when that's required."

In any case, he points out, whatever electrical energy is produced will be used. "That's one of the advantages of having the utility involved. Normally, if industry put the system in, it would have to match the electrical and thermal requirements. In this case, where we use

everything produced, the operation is much more efficient."

Since the cogeneration plant installation will be unmanned, the equipment is instrumented to shut down in case of excess vibration. Another requirement is that the plant have guaranteed emission levels (in line with APCD regulations) as well as proper sound attenuation.

The operating arrangement is that the turbine system will belong to SDG&E but, Applied Energy be responsible for all operating, maintenance and fuel costs. In return, AE will get an electrical credit from SDG&E for everything that's produced by the facility.

Rohr's figures indicate that by going this route, the company will save about \$90,000 a year in steam costs compared to the previous approach. It probably wouldn't be worthwhile to the utility to install this kind of equipment for either electricity or steam alone. But the cogeneration feature, says Hale, makes the overall operation financially attractive.

Projected operating costs, for unmanned operation, are estimated at about \$10,000 a year — including provision for having a technician drive by every day to check out the system. On top of that, maintenance is expected to run about \$25,000 to cover the cost of a normal

3-year overhaul cycle and all routine maintenance recommended by Solar.

According to Hale, those are realistic figures — calculated on the basis of SDG&E operating experience with four Saturn gas turbines on a gas compression station in Riverside County. That is a different kind of application, he admits, but the same machine so that it serves as a good benchmark for what to expect in the way of cost and service requirements.

Solar is enthusiastic about the prospects for cogeneration business in the U.S. whether utility-owned (as in the case of Rohr) or customer-owned (which is more in line with President Carter's concept of cogeneration where the energy facility is wholly owned by the using company). It turns out that the Rohr job is the first in which Solar is supplying gas turbines where the utility owns the plant.

Other cogeneration installations that Solar has worked, newly completed or about to go on line, are all customer-owned. For example, one of these is the Ronzoni plant in Brooklyn, N.Y., rated at 1600 Kw; another is the Georgia Pacific installation in Buchanan, N.Y., which is powered by three Saturns for a total plant rating of 2400 Kw.

Whether industrial customers are better off going to utility-owned or com-

pany-owned facilities is a question of economic tradeoffs and operational requirements. Basically a matter of how you evaluate return on investment versus reduction in operating costs, according to J. Charles Solt, manager of cogeneration applications for Solar. Either route can save users a lot of money.

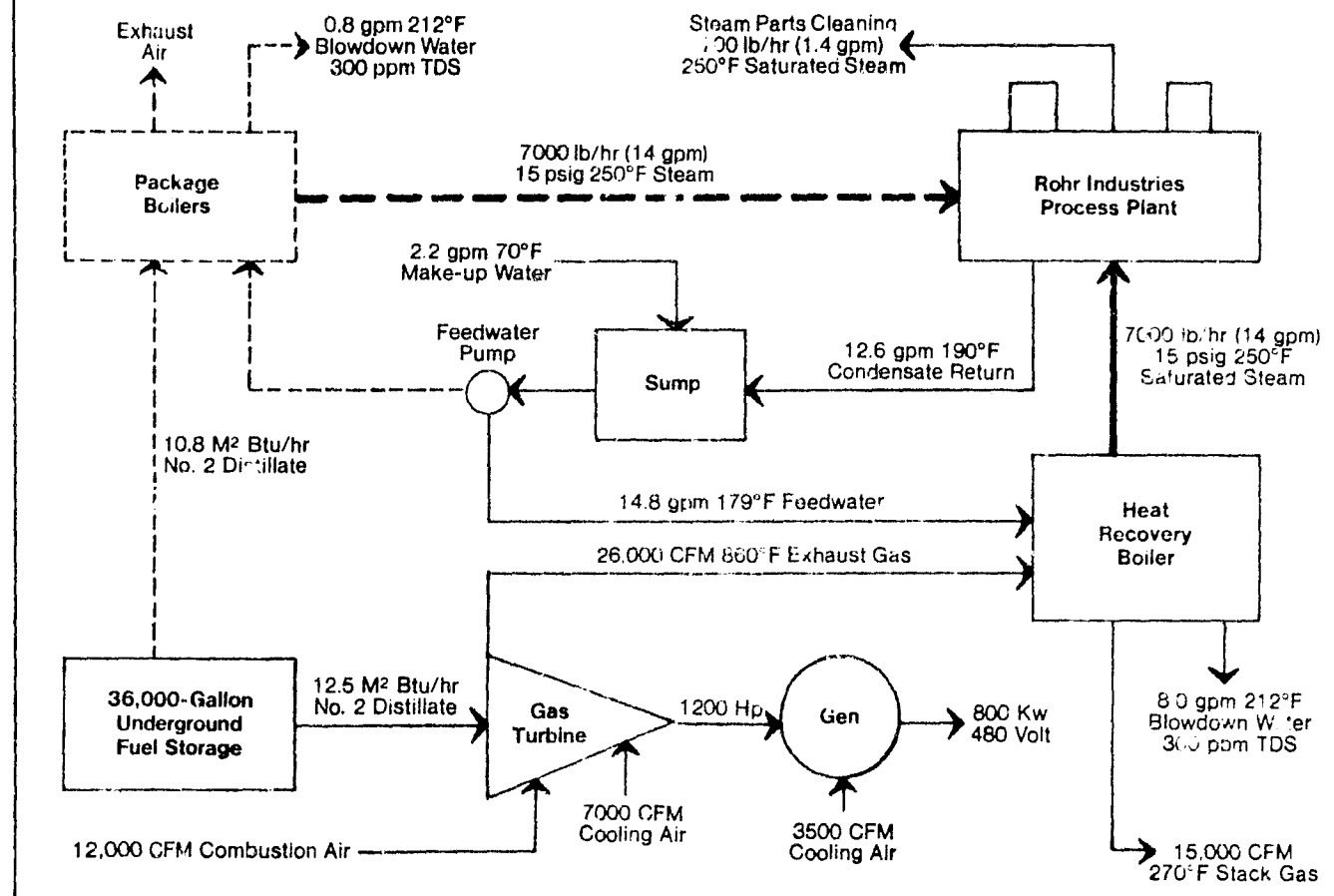
"We've evaluated project costs for dozens of proposed installations which show better than 20% a year return on investment for industrial customers who can use (or sell) the electric power as a byproduct of the steam production," he says. "In other cases, the economies clearly favor a utility-owned plant."

On the utility side, Solt notes there are many customers who would like to receive steam if it were available. "In most cases though, where utilities do provide steam, delivery is from old central plants located in downtown areas — not from new plants because they are seldom downtown and it isn't feasible to transport steam any great distance." Even if they were handy, it's a nuisance to extra a small amount of steam from a large central steam plant so that it is seldom worth the bother. Lot easier to place a small cogeneration plant next to the load.

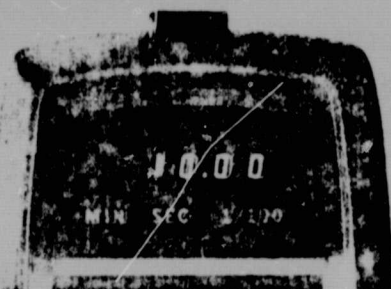
Looking at the longer-range implications of cogeneration, some studies sug-

Cogeneration Plant Should Save Rohr \$90,000 Annually

Utility-owned and operated cogeneration installation will supplant an existing factory boiler plant (dotted lines) to supply Rohr with its process steam requirements — at an estimated \$90,000 a year in fuel savings — while generating electric power for San Diego Gas & Electric's grid system.



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Comparative Evaluation of Rohr Plant Performance

Net heat rate of the Rohr cogeneration plant, powered by a Saturn gas turbine and equipped with unfired heat recovery boiler to produce 15 psi steam, compares favorably with heat rates of much larger Centaur and Mars plant designs.

Performance Parameters	Saturn Plant	Centaur Plant	Mars Plant
Electrical output.....	800 Kw	2670 Kw	7400 Kw
Steam output per hr.....	6795 lb	19,387 lb	36,850 lb
Fuel input per hr x 10 ³	12,950 Btu	38,770 Btu	82,360 Btu
Air mass flow per hr.....	51,760 lb	143,600 lb	300,500 lb
Gas turbine exhaust.....	822 °F	838 °F	785 °F
Stack temperature.....	260 °F	260 °F	260 °F
Net heat rate per kw-hr.....	4825 Btu	4805 Btu	4468 Btu

gest that a broad base plan for installing new electrical generating capacity in the form of cogeneration plants could lead to billions of dollars in savings costs alone. A study by Dow Chemical for ERDA, for instance, projected a potential savings of \$2 to \$5 billion a year which Dow indicated could result in a total reduction in equipment spending of up to \$50 billion by the mid-1980's.

Solt takes such extrapolations with a grain of salt, but nonetheless agrees the gains could be substantial. What is holding things back obviously is the question of government legislative action. "We're discussing hundreds of possible programs with industry and the utilities, but most aren't even in the proposal stage because very few companies are willing to commit themselves until Congress makes a decision.

"As long as there are doubts about what fuels will be available, financial impact of new regulations and so on, people will hang back. There also are more subtle factors: for one, suppose an industrial user decides to build a plant and has excess power it is willing to sell and that the utility is willing to buy. Will the Federal government exempt you from FPC and PUC regulation or will you be classified as an electric utility? President Carter emphasizes he wants such an exemption, but it remains to be seen if the Senate will go along."

Solt is optimistic things will work out. "Worldwide the outlook is excellent. Domestically it depends on what comes out of Congress. But the opportunity to conserve fuel is real, and the opportunity to make money is real, and if it's agreed the former is true the government should be interested."

Certainly Applied Energy is interested and expects to oversee installation of a good many more cogeneration type plants in the future. (The group helped put in facilities of this kind thus far in several places besides Rohr. The others, however, are for government installations. For example, two are in operation now; one at the 32nd St. Naval Station, the other in the Marine Corps Recruit Depot — both in excess of 100,000 lb per hr steam and 20 to 28 Mw. Another

is under construction at North Island Naval Air Station using existing peaking turbines with heat recovery boilers added so the Navy gets the steam.)

Says Hale, "Since Rohr is the first tie-in with industry it is attracting a lot of attention, and we feel we're in a good position to put in more such plants in our areas. Rohr probably will be the smallest. We expect to have a number of future installations up to 25,000 lb per hr steam then there's a gap with the next projects in the 100,000 lb per hr range." Hale stresses the goal is to have any future agreements similar to Rohr's "because most commercial firms don't want to be in the utility business."

Solar, of course, is perfectly happy either way as long as it has a good new market for its turbines. Says Solt, "In Rohr's case, it's the first time we're doing it in that contractual fashion. We have many more instances thus far where the industrial user takes the whole system. A lot of the process companies want to own their own equipment. It would look the same as Rohr's except the electricity would be tied in on the user side of the meter."

He emphasizes Solar is offering a variety of packages, including systems based on the 2700-Kw Centaur and the 7400-Kw Mars. "It's hard to say which size will provide the biggest market. I suspect in unit numbers the Saturn will be the largest, but in total Kw it will be the other way around.

"In terms of industry needs, our series will meet a very large share of cogeneration design requirements. Most utilities talk about enormous cogeneration systems of 100,000 Mw and better. I don't feel there will be many cases for that; maybe a half dozen locations where there are large enough concentrations of plants to justify a large cogeneration facility.

"I suspect the real potential lies with small systems. In the whole size range Solar is concerned with, the largest I'm involved in now is a possible 22 Mw plant that would make use of three 7.4 Mw units and that's probably the largest size plant I'll deal with in the foreseeable future."



SAN DIEGO GAS & ELECTRIC COMPANY

P.O. BOX 1331 SAN DIEGO, CALIF. 92112
(619) 524-1000

JOHN H. WOY
VICE PRESIDENT
RATES & VALUATION

November 30, 1977

PUC 110
Proposal No. 877-E

RECEIVED
Applied Energy, Incorporated

NOV 30 1977

General Manager "cc"

ADVICE 440-E
PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA

San Diego Gas & Electric Company (San Diego) hereby transmits for filing four copies of a "Contract for Special Electric Facilities," dated September 12, 1977, between San Diego and Rohr Industries, Inc. (Rohr), covering the installation and maintenance of special electric facilities for electric service under conditions departing from filed tariff schedules.

This contract, identified as Special Contract 215, provides for the installation and maintenance of special electric facilities which are to be provided by San Diego in addition to, and as enlargements of, the standard facilities which San Diego would install or use in providing normal electric service to Rohr, and which represent additional costs to San Diego over normal equipment installation and maintenance. The special electric facilities are for the purpose of providing electric service to Rohr's critical load (not to exceed 700 kilowatts) in the event of an interruption of San Diego's normal electric service to Rohr. Said special electric facilities consist of, but are not limited to, a breaker, a meter, protective relays and additional equipment, wiring and other necessary hardware. Rohr's critical load consists of a computer and the accessory equipment required for its operation.

The special electric facilities covered by Special Contract 215 are an integral part of a thermally-integrated energy system (TIES) developed by Applied Energy Incorporated (AEI), a subsidiary of San Diego. The TIES facility, or co-generation (two types of energy generated from the same fuel) facility, is to be installed, owned and operated by San Diego and AEI at Rohr's plant located in Chula Vista, California. San Diego has entered into an agreement with AEI for San Diego to install, own and operate an 800 kilowatt oil-fired combustion turbine generating facility, on property leased from Rohr. San Diego will sell the exhaust heat of the turbine to AEI for ultimate use by AEI in an exhaust heat recovery boiler which will generate steam for sale by AEI to Rohr pursuant to a negotiated steam service contract between AEI and Rohr. Except for periods of interrupted normal electric service to Rohr, which would require the turbine to supply electric service to Rohr's critical load, the electric energy generated from the turbine will flow into San Diego's electric distribution system.



SAN DIEGO GAS & ELECTRIC COMPANY

Public Utilities Commission

ORIGINAL PAGE IS
POOR QUALITY November 30, 1977

AEI already operates similar co-generation facilities at military installations in the San Diego area. San Diego believes that the co-generation facility to be installed at Rohr may be the fore-runner of other, similar applications needed to meet the special requirements of San Diego's other commercial or industrial customers. In accordance with Section I.1.b. of San Diego's Rule 2, Special Contract 215 provides for (1) payment of a monthly facility charge of \$775.33, which amount is equal to 1.62% of the estimated installed cost of \$47,860 for the special electric facilities; and (2) payment of the installation and removal costs of \$39,860 should this contract or use of the facilities be terminated by Rohr within five years after the facilities are ready for service. The complex nature of the contractual arrangements with Rohr necessitated the revision of San Diego's standard "Contract for Special Electric Facilities" presently contained in its filed tariffs. Therefore, this filing is considered by San Diego to deviate from its filed tariffs. There are unusual service conditions surrounding the proposed generation facilities; i.e., San Diego in an emergency would, pursuant to contract, allocate the output of the generating unit to Rohr. However, pursuant to Paragraph 9 of the Contract, San Diego retains right to exercise its Rules 14 and 14.2 as filed with this Commission in the event there is a shortage in San Diego's energy supply or interruption of electric service to the standard facilities.

San Diego believes, and therefore alleges, that the revenue from this contract is compensatory and that the fulfillment of said contract under the terms thereof will not result in a burden on other ratepayers. San Diego further believes, and alleges, that the establishment of said contract will not establish any unreasonable difference as to rates, charges, service, facilities, or in any other respect, as prohibited by Section 453 of the Public Utilities Code.

Pursuant to Section X.A. of General Order 96-A, Special Contract 215 is hereby submitted for filing. Authorization of the Commission to supply the service specified under the terms and conditions of this contract with Rohr is hereby requested.



SAN DIEGO GAS & ELECTRIC COMPANY

Public Utilities Commission

-3-

November 30, 1977

A copy of this advice letter is being furnished to the following in accordance with Section III-G of General Order 96-A:

**Anza Electric Cooperative, Inc.
City of San Diego
Pacific Gas and Electric Company
Southern California Edison Company
Southern California Gas Company**

SAN DIEGO GAS & ELECTRIC COMPANY

JOHN H. WOY

Vice President-Rates & Valuation

Enclosure